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EXPLORATORY STUDIES OF MECHANICAL CYCLING FATIGUE BEHAVIOR OF MATERIALS FOR THE SUPERSONIC TRANSPORT

by D. N. Gideon, C. W. Marschall, F. C. Holden, and W. S. Hyler

Prepared under Contract No. NASr-100(01) *by*
BATTELLE MEMORIAL INSTITUTE
Columbus, Ohio
for

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EXPLORATORY STUDIES OF MECHANICAL CYCLING FATIGUE BEHAVIOR OF MATERIALS FOR THE SUPERSONIC TRANSPORT

SUMMARY

This report describes an exploratory investigation of the fatigue behavior of two materials considered as skin materials for the supersonic transport (SST). The materials are AM-350 CRT steel and triplex-annealed Ti-8Al-1Mo-1V alloy.

The three facets to the program are (1) base fatigue strength of the materials, (2) crack-propagation behavior and (3) residual static strength. In each case many variables have been examined that are related to the operating conditions of the SST. For example, base fatigue strength has been examined on unnotched and notched specimens at temperatures ranging from -110 F to 550 F. Similarly, the effect of prior stressed exposure at 550 F on fatigue strength has been evaluated for exposure times up to 3000 hours for AM 350 alloy.

Crack-propagation studies were conducted on center-notched sheet specimens of AM-350 alloy with variables evaluated such as alternating stress amplitude, test temperature, cyclic rate, specimen orientation, and prior stressed exposure. As expected, alternating stress amplitude and test temperature appreciably affect crack-propagation rates, whereas, for times up to 1000 hours, stressed exposure was not important.

Residual-static-strength measurements also were made from center-cracked specimens of AM-350 alloy. Crack length and test temperature were found to be important variables, whereas stressed exposure and conditions under which the fatigue cracks were grown were found to be unimportant variables.

Although in this first year's program more emphasis was placed upon the stainless steel than on the titanium alloy, no behavior was observed that would rule out the use of either material for the SST application.

INTRODUCTION

The National Aeronautics and Space Administration is engaged in research programs that will provide useful information in the development of a commercial supersonic transport (SST). Some of this effort is being accomplished within the NASA organization; other programs, such as the one presently reported, represent sponsored research so directed as to complement the NASA effort.

One of the problem areas in the SST development concerns the selection of structural materials. As with most aircraft structures, one of the factors is fatigue. Accordingly, the present program is concerned with the basic fatigue behavior of two potential SST skin materials: AM-350 CRT stainless steel and Ti-8Al-1Mo-1V alloy.

The conditions within which the SST will operate are such that certain portions of the structure will be subjected at cruise to temperatures of the order of 550 F. At other times in flight, temperatures well below freezing may be encountered. Accordingly, fatigue damage may occur over a broad temperature range. For this reason, exploration of fatigue behavior at 550 F, room temperature, and at -110 F was of interest.

In the SST, cruise will represent an appreciable fraction of each flight. In this regime, the important exposure conditions for the structure will involve elevated temperature at a nominal 1-g stress level. The long-time exposure under these conditions may lead to changes in the metallurgical structure of the materials that in turn could affect mechanical behavior. A part of this program was to determine whether such exposure would affect the fatigue performance of these two alloys. In this program, an exposure temperature of 550 F was employed. One-g stress levels of 40 and 25 ksi were used for the AM-350 and the Ti-8Al-1Mo-1V alloy, respectively.

The objective of the Battelle program is to explore many of the factors that may influence fatigue behavior of these materials. Part of this effort concerned fatigue-crack propagation and residual static strength; part concerned exploration of the base fatigue strength of the materials. The importance of metallurgical instability was examined in each of these aspects.

As will be evident in subsequent sections, a large number of variables have been studied, in some cases to a very limited extent. It was intended to examine many variables in order to determine whether specific problems might be disclosed that could be examined to a greater extent in subsequent work.

EXPERIMENTAL DETAILS

Materials

Material used in this work was provided by Langley Aeronautical Laboratories from a large quantity of sheet material specifically procured for NASA programs. Three sheets of AM-350 CRT and of triplex-annealed Ti-8Al-1Mo-1V were received. Manufacturer's chemical-analysis and mechanical-property data, together with detailed tensile data obtained at Battelle, are listed in Appendix A.

For room-temperature tests, seven tensile specimens were cut from a section near the center of each of the three sheets to check (1) the effects of rolling direction, (2) the reproducibility of tensile properties from one sheet to another, and (3) the consistency of tensile properties at various points within each sheet. Specimens were 8 by 1 inch, with a reduced section 2 inches long by 0.5 inch wide in the titanium alloy, and 0.375 inch wide in the AM-350 steel. The test specimens were cut from the three sheets according to the sketch shown in Figure 1. The specimens were loaded in tension at a head speed of 0.02 inch per minute. Stress-strain curves were plotted autographically, with strain being measured from an electric-resistance gage (SR-4, Type A1. Tests also were conducted at -110 F and at 550 F on longitudinal specimens from one sheet of each material.

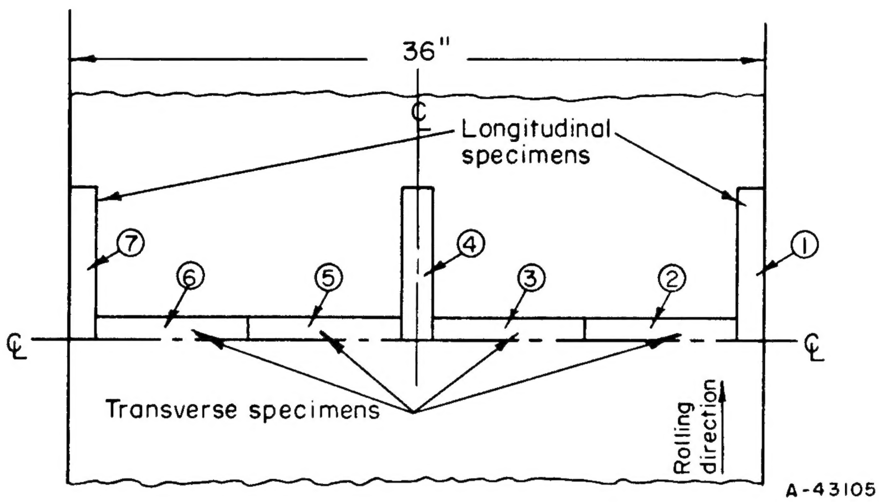

FIGURE 1. LAYOUT OF TENSILE-TEST SPECIMENS

The tensile data as listed in Appendix A show the following trends:

(1) In regard to primary rolling direction, there were significant differences in strength between longitudinal and transverse specimens. For example, for both alloys tensile yield strength values were less for transverse specimens than for longitudinal specimens. This statement is also true for ultimate strength for the titanium alloy, whereas, transverse ultimate strength of AM-350 was greater than that in the longitudinal direction.

(2) Reproducibility of properties from one sheet to another was good. For example, sheet-to-sheet variations in yield strength for AM-350 were less than ± 1 per cent; for Ti-8Al-1Mo-1V alloy, the same property varied about ± 2 per cent.

(3) Consistency of tensile properties of various points within each sheet also was quite good. Variations cited above are also appropriate in regard to mechanical-property consistency within a sheet.

Table 1 contains a summary of the longitudinal properties of the two alloys at three temperatures. It is seen for all strength characteristics that the properties increase with decreasing temperature.

TABLE 1. SUMMARY OF TENSILE STRESS-STRAIN DATA FOR LONGITUDINAL SPECIMENS OF AM-350 STEEL AND Ti-8Al-1Mo-1V ALLOY

Temperature, F	0.2 Per Cent Offset Yield Strength, ksi SS,Ti	Ultimate Tensile Strength, ksi SS,Ti	Elongation in 2 Inches, per cent SS,Ti	Modulus of Elasticity, 10^6 psi SS,Ti
		AM 350		
-100	221	272.5	20.2	28.1
RT	221	233	21.1	27.8
550	184	201	3.7	25.2
		Ti-8Al-1Mo-1V		
-100	165.5	178.5	12.0	20.0
RT	139.7	152.3	12.9	18.8
550	98.0	124.5	9.5	16.7

Specimen Design and Fabrication

Three types of specimens have been employed in this program: an unnotched specimen, an edge-notched specimen, and a center-notched specimen. Details of each specimen are shown in Figure 2.

The unnotched specimen has a continuous radius section that was machined in by a milling operation. About 10 specimens were clamped together during this operation. The machined surfaces were carefully polished with 400-grit emery paper to eliminate the longitudinal machining marks. The minimum section width, D, was 0.580 inch for AM 350 alloy and 0.800 inch for the titanium alloy.

Edge-notched specimen details were proportioned to provide geometrically the same severity of notch used on a number of Battelle and NASA programs[1,2]*. The theoretical stress-concentration factor of the notch, K_t, was 4.0. These specimens also were machined in stacks of about 10 specimens. The notch was carefully machined with a milling cutter and carefully polished with a rotating copper wire with slurry, to eliminate machining marks.

Specimens containing the center notch were used for the crack-propagation studies. As noted in the figure, the center notch was to be 0.010 inch wide and 0.120 inch long. Fabrication of the center-notched specimens involved three steps:

(1) Milling of the external dimensions and drilling and reaming the holes for loading

(2) Roughing in a slit in each specimen with an electrical sparking apparatus, using a jig to insure centering and alignment of the slit in the specimen (see Figure 3)

(3) Grinding or lapping the ends of the slit in each specimen to achieve good geometrical definition of the slit ends, and specified length and centering of the slit (see Figures 4 and 5).

Some 60 AM-350 center-notched specimens were made. Examination of the finished notches showed them to be uniformly good and to have radii of 0.0045 inch; the slit lengths were 0.122 ± 0.002 inch. The elastic-stress-concentration factor for these specimens is estimated to be 7.8, using relations derived by Inglis[3] and by Dixon[4], as reported by Gerard[5].

Equipment

All fatigue testing was conducted in Krouse Direct Stress Fatigue machines of 5,000 or 10,000-pound capacity. These machines operate at 1725 and 1200 cpm,

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* References are given on page 50.

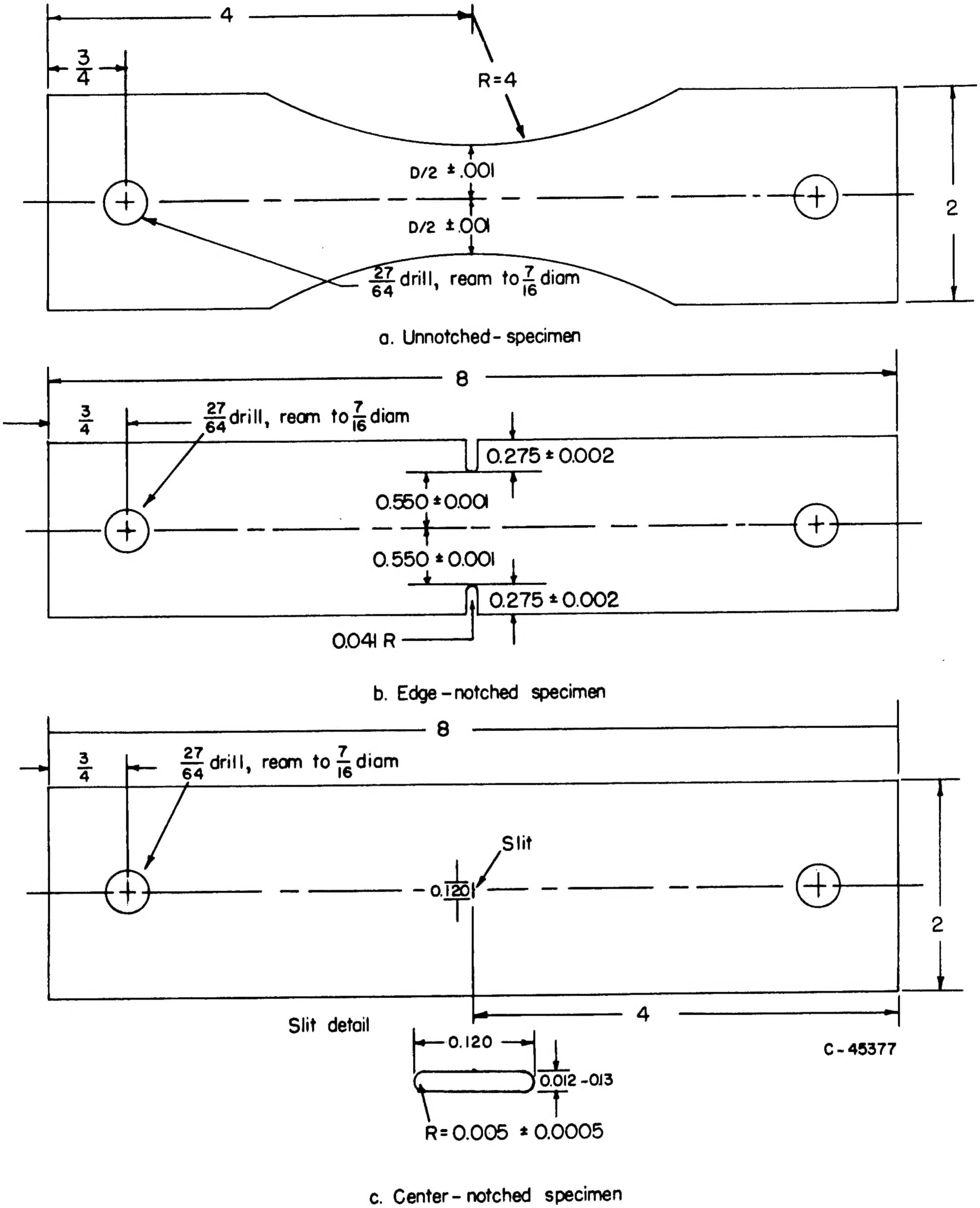

FIGURE 2. FATIGUE-SPECIMEN DETAILS

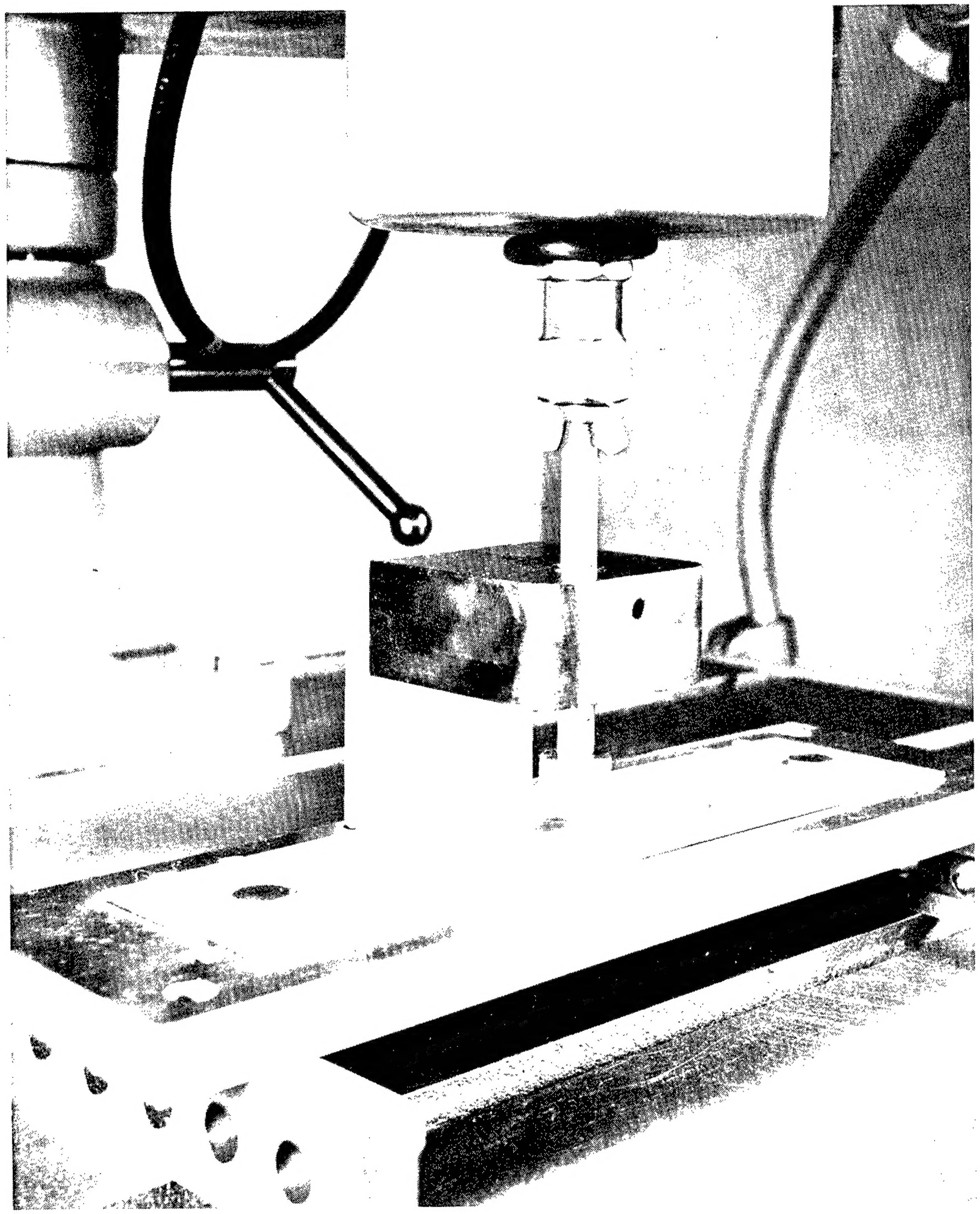

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FIGURE 3. CLOSE-UP VIEW OF ELECTRICAL-SPARK APPARATUS FOR MAKING CENTER-NOTCHED SPECIMENS

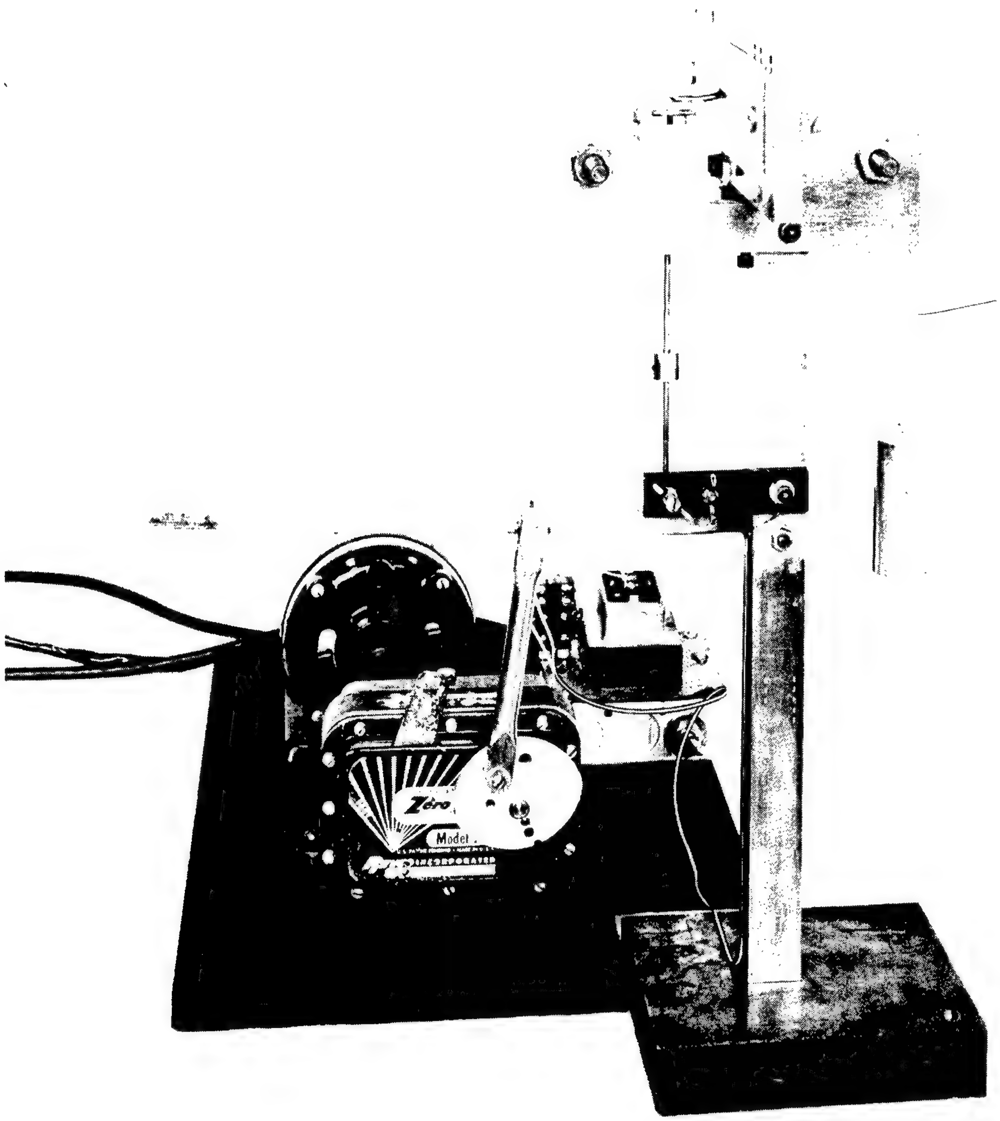

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FIGURE 4. APPARATUS FOR FINISHING ROOT OF CENTRAL NOTCHES

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FIGURE 5. CLOSE-UP VIEW OF NOTCH-FINISHING APPARATUS

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respectively. The smaller capacity machines are equipped with automatic hydraulic load maintainers that monitor test loads on each specimen. Accuracy of load setting and maintenance is about 3 per cent of the maximum test load.

For specimens that were stressed in compression for part of the cycle, guide plates were used of a design similar to those used at Langley Aeronautical Laboratories. These consisted of graphite plates held in contact with the specimen by steel pressure plates and pressure screws mounted in a rigid frame. For tests involving elevated temperature, heater elements were sandwiched between a graphite plate and an insulator plate. This simple heating means provided excellent uniformity of temperature.

Tests at -110 F were conducted with the specimen in a box made of 2-inch-thick polyurethane foam insulation with inside dimensions about 6 by 8 by 12 inches. The box is kept full of solid CO_2 during experiments; liquid nitrogen is fed from a 110-liter self-pressurized Dewar through a solenoid valve and plastic tubing to the specimen. The liquid nitrogen is directed through holes in the frame and the pressure plate of the antibuckling jig against the graphite plate on the side away from the specimen. A control thermocouple is located in a groove on the same side of the graphite so that liquid nitrogen strikes the thermocouple bead. When the thermocouple signal indicates the need for coolant, a controller actuates the solenoid valve, permitting liquid nitrogen to flow. Since the liquid-nitrogen flow is directed toward the control thermocouple, the flow stops abruptly. A second thermocouple on the opposite side of the specimen is located in a hole in the graphite plate within about 1/32 inch of the specimen surface at the center point of the specimen face. This second thermocouple indicates a temperature during experiments which is within ± 2 F of the desired temperature and which fluctuates only a small fraction of 1 F (less than 1/2 F).

Equipment that was used to expose specimens to elevated temperature and stress prior to fatigue testing was essentially a recirculating-air furnace. A photograph of the unit is shown in Figure 6. The furnace was designed for temperatures up to 1000 F, and has a capacity of 80 specimens 8 inches in length. Dead-weight loads are applied to the specimens through five independent lever-arm systems. Each lever arm applies a load to two rows of eight specimens each attached in series in the form of chains as shown in Figure 7.

The furnace is heated by means of two 7.5-kw wire resistance heaters located at the rear. A radial-flow fan located directly below the heaters recirculates the air up past the heaters and into the top of the furnace cavity. Chromel-Alumel thermocouples located throughout the furnace indicate temperature variations to be within ± 15 F at 550 F. The temperature is controlled by a Brown pyrovane controller and is recorded by a Leeds and Northrup 12-point recorder. A second controller set at 570 F is placed in the circuit to serve as a precaution against overshooting the desired temperature through a malfunction of the main temperature controller. About 7 kw is required to maintain a temperature of 550 F.

Load calibrations were made by placing a test bar with SR-4 strain gages in series with each chain of specimens. After calibration, the test bars were replaced with test specimens without changing the load on the respective lever.

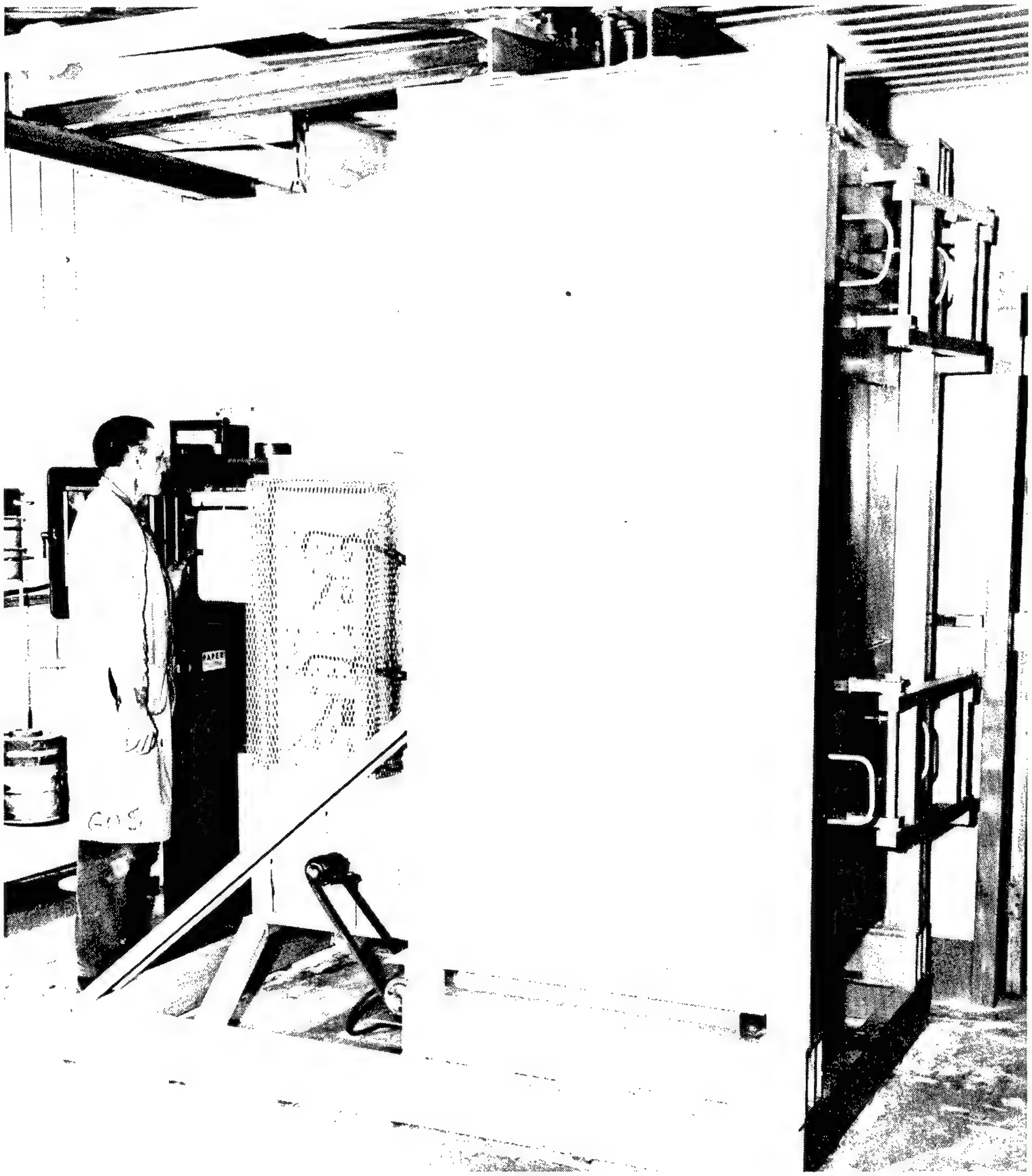

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FIGURE 6. STRESS-TEMPERATURE EXPOSURE EQUIPMENT

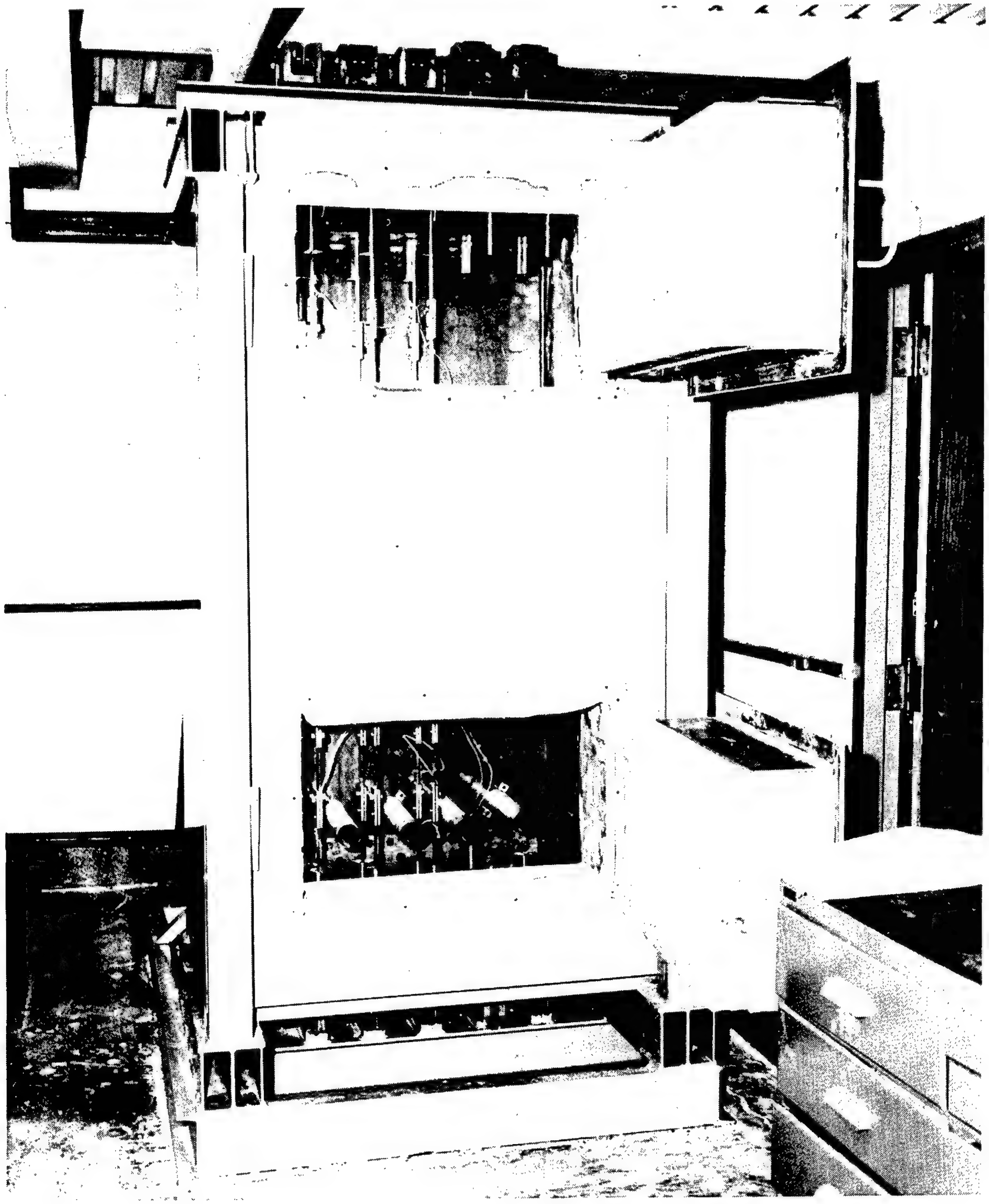

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FIGURE 7. SPECIMEN-EXPOSURE TECHNIQUE

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CRACK PROPAGATION AND RESIDUAL STATIC STRENGTH

There are a variety of conditions under which a fatigue crack may grow when consideration is given to the flight envelope of a supersonic transport. The strength of a structure containing a fatigue crack will vary also as a consequence of environmental factors associated with the flight envelope.

For this reason a wide variety of conditions were examined, primarily to establish which might have an important effect on crack propagation and on residual strength. Among the variables examined were the following: alternating stress amplitude, cyclic frequency, fatigue-cracking temperature and static-test temperature, orientation of specimen, and prior stressed exposure. In the present program, only AM-350 alloy was studied. However, it is planned to examine the titanium alloy in a similar way during the second year of the program.

Crack-Propagation Studies

The study of fatigue-crack propagation was carried out in conjunction with the residual-strength studies. In the latter effort, fatigue-cracked specimens with tip-to-tip crack lengths of 3/16-, 3/8-, and 3/4-inch were evaluated. During preparation of the center-cracked specimens for the residual-strength studies, crack-growth measurements were made on each specimen. Attention was given to specimens containing center cracks of about 3/4-inch length. Accordingly, crack-propagation information is available on the AM-350 alloy to crack lengths of about 3/4 inch (an ℓ/W of about 0.375). All cracking was done at a mean stress of 40 ksi.

Most of the specimens were cracked in a 10,000-pound Krouse fatigue machine that was operated at 1200 cpm. During cracking, the net section stresses were held constant within ± 10 per cent of the nominal values. Crack-propagation measurements were made at room temperature by preparing cellulose-acetate replicas of the crack; from the replicas, crack lengths were accurately measured to the nearest 0.001 inch. At -110 F and at 550 F, the measurements were made with a measuring microscope focused on the crack through a window in the enclosure.

From the experimental data, plots were made of crack length as a function of cycles. As shown in Figure 22 in a succeeding section, the resulting curves show rather clearly the effect of the 10 per cent stress variation on crack propagation. It is readily apparent that crack-propagation rates would have been much higher had tests been run at a constant load.

In order to determine the effects of the several variables on crack propagation, the data have been analyzed to determine propagation rates for two lengths of crack, 1/4 and 5/8 inch. In this analysis, the curves were drawn to minimize effects of the propagation-rate changes that occur with load readjustment. The resulting data are shown in Table 2. Also included in this table is a summary of the number of cycles to initiate cracks of a length of 0.130 inch and the number of cycles then to propagate a crack from its initial length to 0.25 and 0.625 inch.

TABLE 2. CRACK-PROPAGATION DATA FOR AM-350 STEEL

Test Condition	Orientation	Propagation Rate (μ in./cycle) for Indicated Crack Lengths 0.25 In.	0.625 In.	Total Cycles to Indicated Crack Lengths (Initiation) 0.130 In.	0.25 In.	0.625 In.
1. Unexposed, RT, 49.3 ASA[(a)], 34 cpm	L	57	66	400	2,200	8,400
2. Unexposed, RT, 49.3 ASA, 120 cpm	L	49	82	400	3,250	8,800
3. Unexposed, -110 F, 30 ASA, 1200 cpm	L	15	30	4,350	17,800	34,300
	L	14	31	8,100	17,150	36,400
4. Unexposed, RT, 10 ASA, 1200 cpm	L	3.1	5.8	-[(b)]	190,750	280,100
5. Unexposed, RT, 15 ASA, 1200 cpm	L	6.5	9.0	17,800	41,000	85,000
	L	7.8	14	38,700	63,000	97,600
6. Unexposed, RT, 25 ASA, 1200 cpm	L	17	--	--	15,500	--
	T	15	--	7,700	15,800	--
7. Unexposed, RT, 30 ASA, 1200 cpm	L	--	--	3,750	--	--
	L	--	--	3,750	--	--
	L	--	--	5,300	--	--
	L	14	--	5,000	14,250	--
	L	23	--	3,800	11,450	--
	L	21	--	4,200	11,650	--
	L	22	40	4,900	12,500	24,900
	L	22	37	3,500	8,000	21,540
	L	29	37	3,500	11,700	23,200
	L	19	30	4,000	11,200	26,000
	T	--	--	2,950	--	--
	T	26	--	4,100	10,200	--
	T	25	44	2,600	9,000	19,800
8. Unexposed, RT, 55 ASA, 1200 cpm	L	41	75	450	4,150	10,150
	L	41	73	800	4,075	10,350
9. Unexposed, 550 F, 30 ASA, 1200 cpm	L	26	68	2,400	9,800	16,900
	L	27	73	2,000	8,300	16,300
10. Exposed, RT, 49.3 ASA, 34 cpm	L	30	75	450	5,000	9,800
11. Exposed, RT, 49.3 ASA, 120 cpm	L	56	83	250	3,500	8,750
12. Exposed, RT, 15 ASA, 1200 cpm	L	7.3	11	12,600	35,000	69,000
13. Exposed, RT, 30 ASA 1200 cpm	L	--	--	4,100	--	--
	L	--	--	3,150	--	--
	L	--	--	3,500	--	--
	L	--	--	4,250	--	--
	L	24	--	--	10,000	--

TABLE 2. (Continued)

Test Condition	Orientation	Propagation Rate (μin./cycle) for Indicated Crack Lengths 0.25 In.	0.625 In.	Total Cycles to Indicated Crack Lengths (Initiation) 0.130 In.	0.25 In.	0.625 In.
	L	25	--	--	10,400	--
	L	23	--	3,900	11,700	--
	L	19	34	5,200	13,400	26,200
	L	25	38	3,400	10,600	22,400
	L	22	35	2,700	9,100	21,000
14. Exposed, RT, 55 ASA, 1200 cpm	L	42	79	--	4,200	10,300
	L	45	85	600	3,850	9,250
15. Exposed, 550 F, 30 ASA, 1200 cpm	L	27	72	2,450	6,950	14,750

(a) ASA denotes alternating stress amplitude in ksi.

(b) Dash indicates either insufficient or no data available to determine the desired value.

In the following discussion, reference is made to exposed and unexposed specimens. For AM-350 alloy, exposure means that specimens were subjected to 550 F and 40-ksi steady stress for 1000 hours or more. For center-notched specimens evaluated to date, specimens had been exposed only for 1000 hours.

The Effect of Alternating Stress Amplitude

The effect of alternating stress amplitude on crack propagation was observed for three conditions:

(1) Unexposed, longitudinal specimens fatigue cracked at room temperature and 1200 cpm

(2) Exposed, longitudinal specimens fatigue cracked at room temperature and 1200 cpm

(3) Unexposed, transverse specimens fatigue cracked at room temperature and 1200 cpm.

Figures 8 and 9 show data taken from Table 2 that are pertinent. In these figures are plotted alternating stress versus rate of crack propagation for two lengths of the growing crack (i. e., 1/4 and 5/8 inch). Figure 8 shows data for unexposed specimens, whereas Figure 9 is for exposed specimens. As noted, most of the testing was carried out on longitudinally oriented specimens. From these figures come a number of observations:

(1) As expected, an increase in alternating stress amplitude results in a higher rate of crack propagation.

(2) The rate of crack propagation is greater the longer the crack (within limits of the experimental data, 3/4 inch), even though the net-section stresses are held constant within ± 10 per cent as the crack progresses.

(3) There is variability or scatter in crack-propagation rates for replicate tests, consequently, since at most stress levels one or two specimens were tested compared to many at 30 ksi, the functional relationship between alternating stress amplitude and propagation rate is not clear.

(4) Evidence from the few tests on specimens with major axis transverse to the principal rolling direction does not clearly indicate that orientation affects crack propagation. The slight tendency to suggest that this is so will be evaluated more thoroughly in the second year's program.

Another way of looking at the data on crack propagation is shown in Figures 10 and 11 for unexposed and exposed specimens, respectively. In these figures plotted on stress amplitude-log cycles coordinates are data representing the total number of

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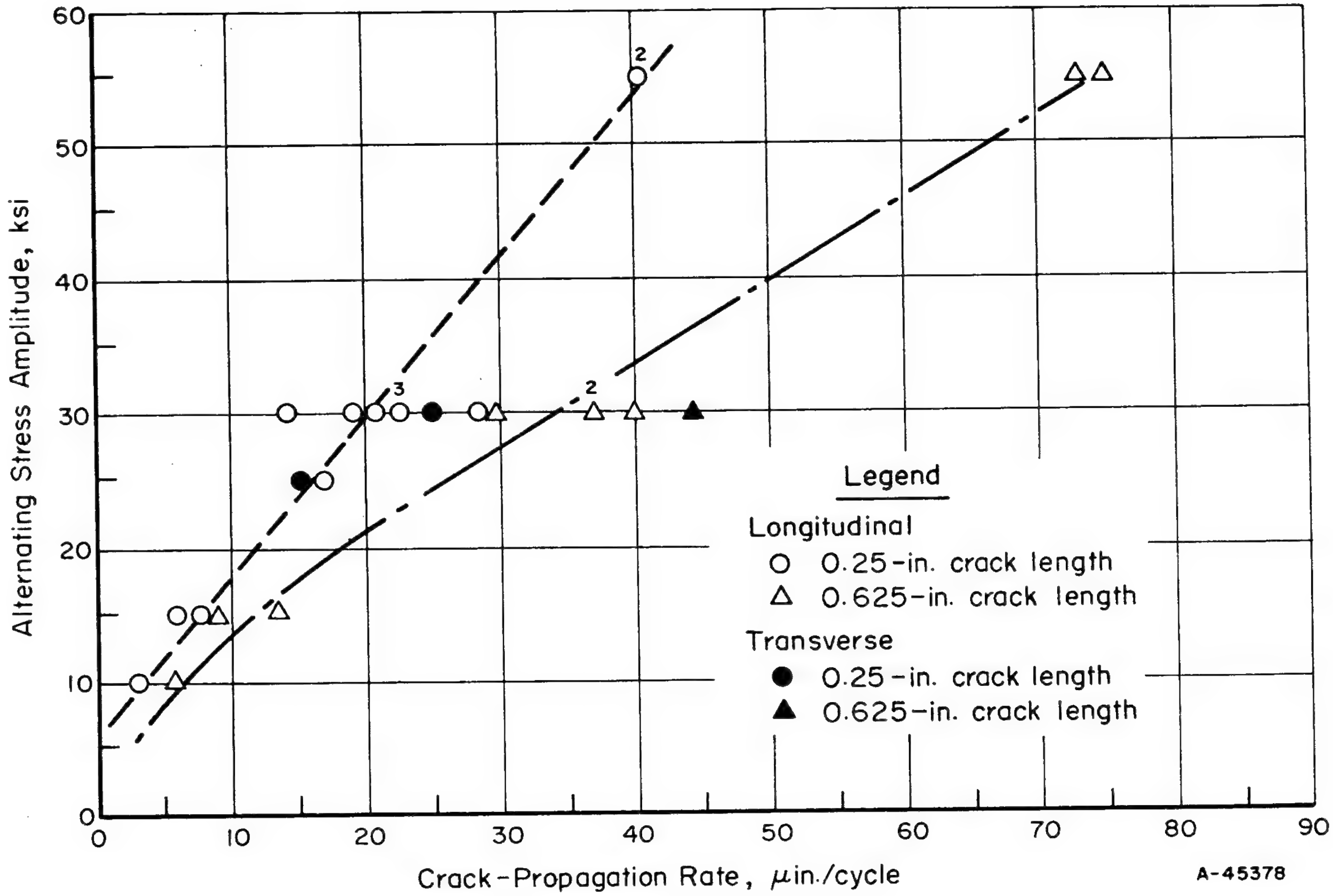

FIGURE 8. EFFECT OF ALTERNATING STRESS AMPLITUDE ON THE CRACK-PROPAGATION BEHAVIOR OF UNEXPOSED AM-350 STEEL, 40-KSI MEAN STRESS AND 1200 CPM

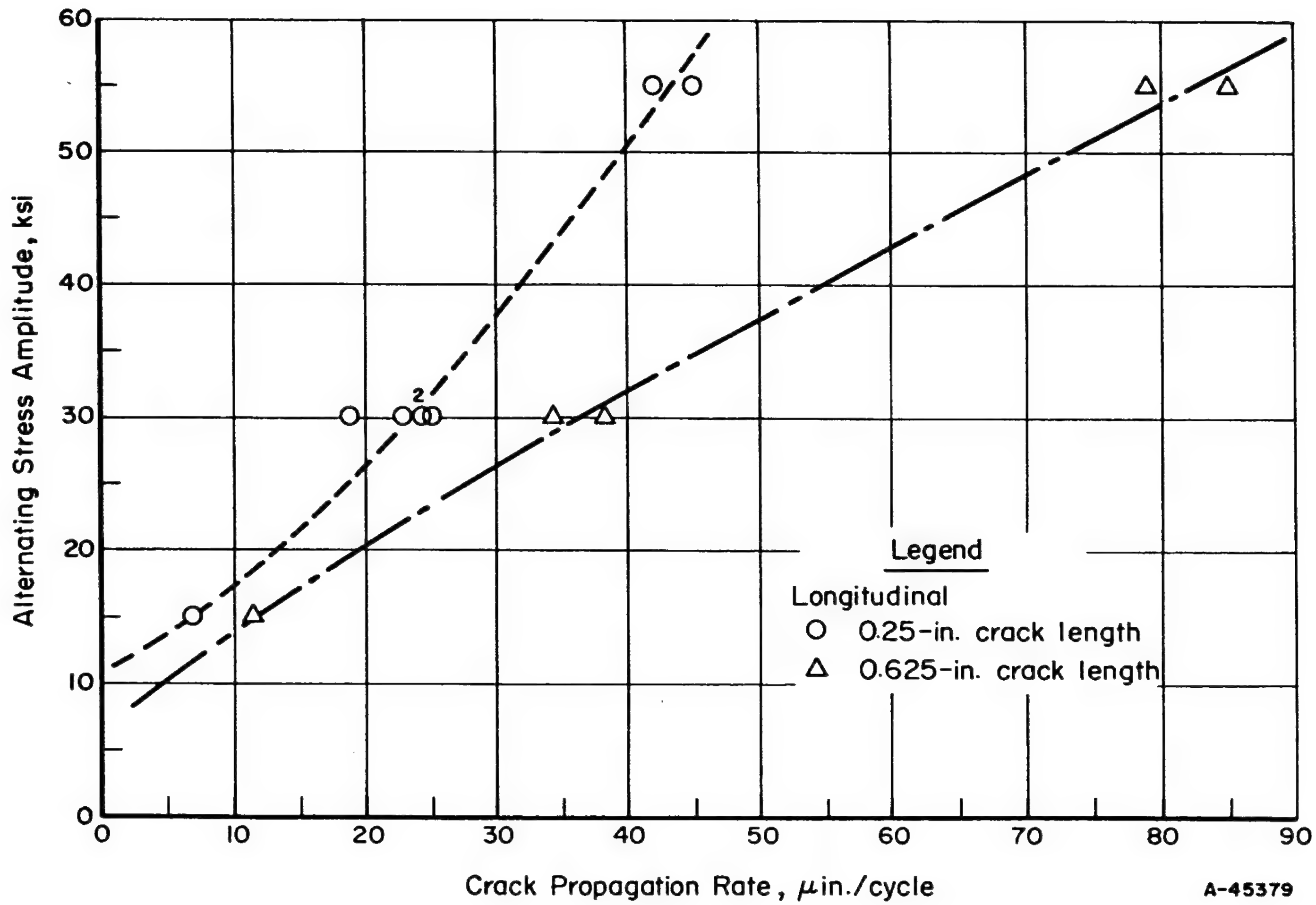

FIGURE 9. EFFECT OF ALTERNATING STRESS AMPLITUDE ON THE CRACK PROPAGATION BEHAVIOR OF EXPOSED AM-350 STEEL, 40-KSI MEAN STRESS AND 1200 CPM

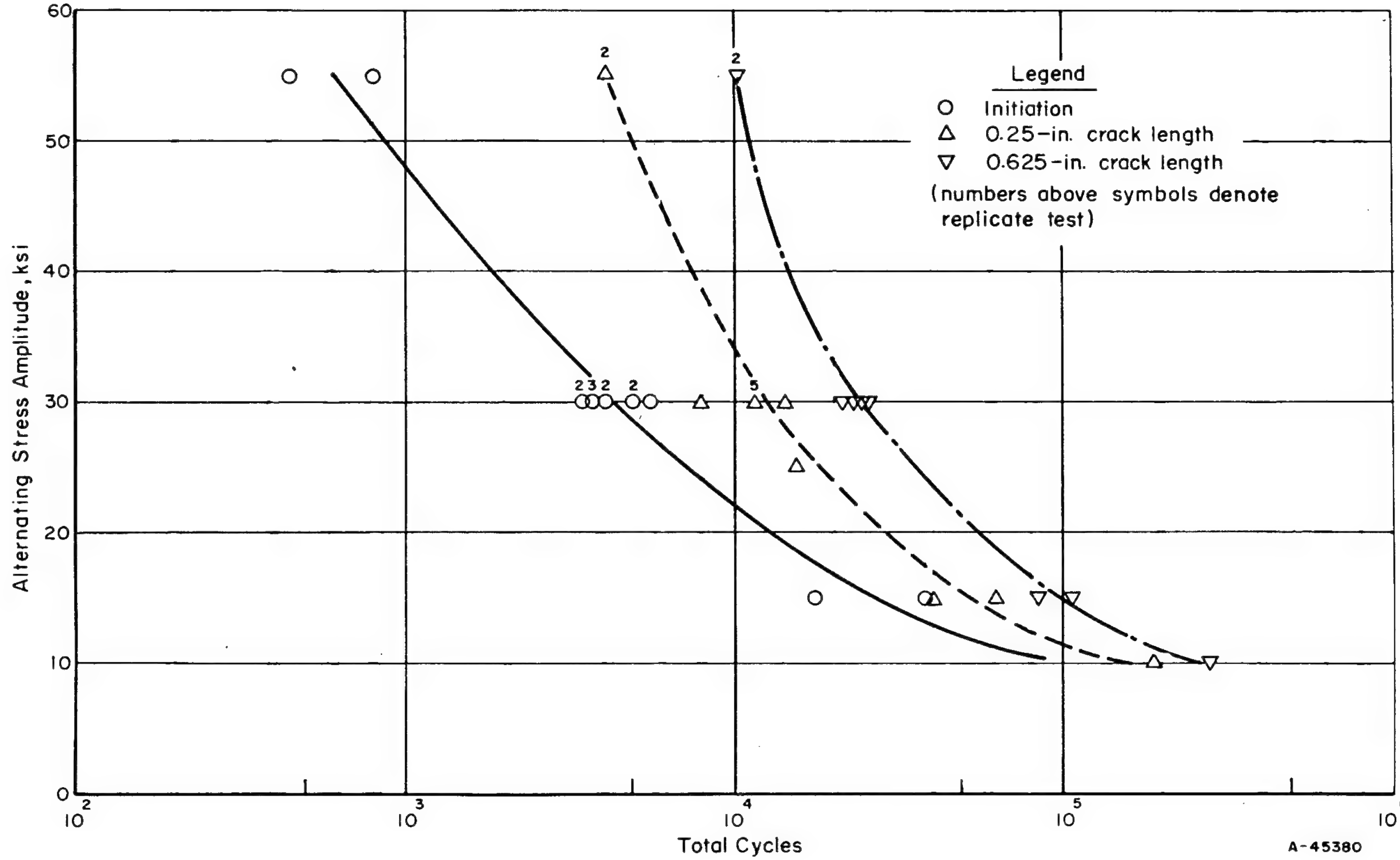

FIGURE 10. EFFECT OF ALTERNATING STRESS AMPLITUDE ON CRACK PROPAGATION IN LONGITUDINAL, UNEXPOSED AM-350 STEEL SPECIMENS AT ROOM TEMPERATURE AND 1200 CPM

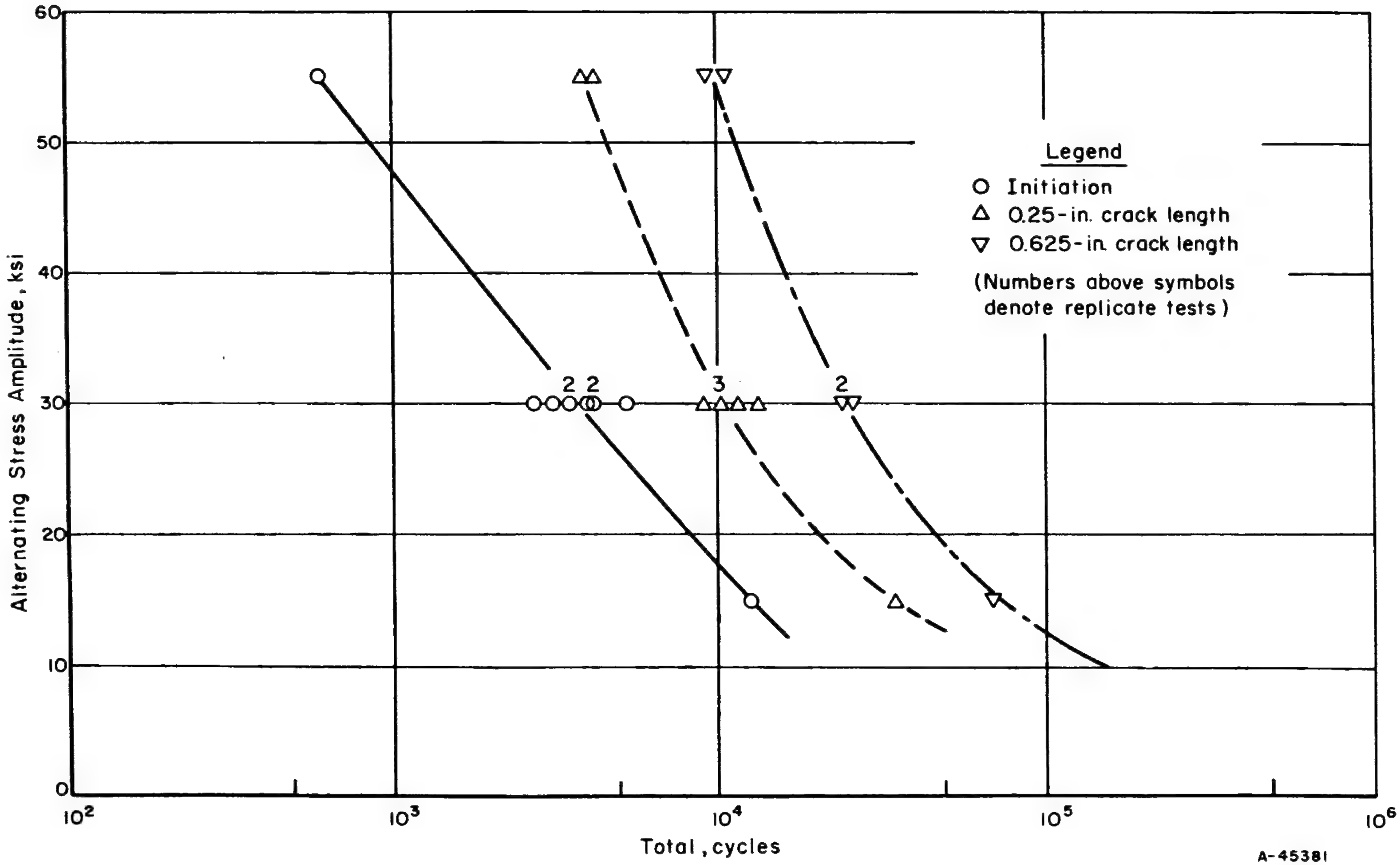

FIGURE 11. EFFECT OF ALTERNATING STRESS AMPLITUDE ON CRACK PROPAGATION IN LONGITUDINAL, EXPOSED AM-350 STEEL SPECIMENS AT ROOM TEMPERATURE AND 1200 CPM

cycles to (1) crack initiation (a crack with tip-to-tip length of 0.130 inch), (2) a crack length of 0.25 inch, and (3) a crack length of 0.625 inch. The curves through the data points resemble S-N curves for failure. From both figures it is probable that at an alternating stress not too far below 10 ksi fatigue cracks may not initiate, or if they do, propagation will be slow or nonexistent.

It is very interesting to note that at high stress amplitudes crack propagation is a major portion of specimen life; whereas at low stress amplitudes, the crack propagation period is a relatively shorter period in specimen lifetime. This is illustrated in the following tabulation obtained from data shown in Figure 10:

Alternating Stress Level, ksi	Cycles at Initiation	Cycles to 0.625-Inch Crack	Lifetime for Which Specimen Is Cracked[a], per cent
55.0	600	10,400	94
30.0	3,400	20,500	83
15.0	27,000	97,000	78

(a) Based upon lifetime at 0.625 crack length.

The Effect of Cycling Rate

It was hoped that a few tests at various cyclic frequencies might be helpful in determining whether frequency was a factor to consider further. The experiments were run at an alternating stress level of 49.3 ksi, 40-ksi mean stress on exposed and unexposed specimens. Frequencies of 34 and 120 cpm were examined. Table 3 shows crack-propagation rates obtained at two levels of crack length(s) compared with similar data obtained from the curves of Figures 8 and 9 on specimens run at 1200 cpm. It is rather obvious from the table, if one considered all of the data for tests run at the two lower frequencies, that on the average, higher rates of crack propagation attend lower frequency testing. If one considers the merits of the data at each frequency, the conclusion appears to be that the frequency effect is unresolved because of potentially large scatter in the data.

The Effect of Temperature

Data showing the effect of temperature on fatigue-crack-propagation rates are summarized, in Table 4. It is rather clear from this table that at the same stress amplitude the rate of crack propagation at -110 F is on the low end of the scatter band of crack-propagation rate for specimens tested at room temperature. Also specimens tested at 550 F had propagation rates either on the high end of the band or significantly higher than were propagation rates at room temperature.

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TABLE 3. DATA ON CRACK-PROPAGATION RATES AT THREE CYCLING FREQUENCIES FOR LONGITUDINAL AM-350 STEEL SPECIMENS TESTED AT 49.3-KSI ALTERNATING STRESS AMPLITUDE AND ROOM TEMPERATURE

Crack Length, inch	Crack-Propagation Rates, μin./cycle, for Indicated Frequencies		
	34 CPM	120 CPM	1200 CPM
		Unexposed	
0.25	57	49	36
0.625	66	82	65
		Exposed	
0.25	30	56	39
0.625	75	83	71

TABLE 4. DATA OBTAINED AT THREE TEMPERATURES ON FATIGUE-CRACK-PROPAGATION RATES IN LONGITUDINAL AM-350 SPECIMENS AT 30-KSI ALTERNATING STRESS AMPLITUDE AND 1200 CPM

Crack Length, inch	Propagation Rates, μin./cycle, for Indicated Temperatures		
	-110 F	RT	550 F
		Unexposed	
0.25	16	14(a)	26
0.25	14	21(b)	27
0.25	--	29(c)	--
0.625	30	30	68
0.625	31	37	73
0.625	--	37	--
0.625	--	40	--
		Exposed	
0.25	--	19(a)	27
0.25	--	23(b)	--
0.25	--	25(c)	--
0.625	--	34	72
0.625	--	34	--
0.625	--	38	--

(a) Minimum value of specimens tested.
(b) Mean value of specimens tested.
(c) Maximum value of specimens tested.

Thus, temperature is an important variable on crack propagation. Examination of initiation and propagation data (from Table 2) for specimens whose propagation-rate data are summarized in Table 4 shows the following: (1) initiation of cracks occurred earliest in those specimens tested at 550 F and latest in those specimens tested at -110 F; (2) the number of cycles to reach a crack length of 5/8 inch was least for specimens tested at 550 F, greatest for those tested at -110 F. This behavior, together with the propagation-rate information, substantiates the fact that fatigue strength of the material increases with a decreasing temperature.

The Effect of Exposure

In the preceding sections, data on exposed as well as unexposed specimens have been presented both graphically and in tables. However, discussion of the effect of exposure has been deferred until this section.

Consider first Figures 8 and 9. These figures, when carefully compared, show that the crack-propagation rates for specimens exposed for 1000 hours at 40 ksi and 550 F are slightly higher than those for unexposed specimens tested at comparable alternating stress amplitudes. Figures 10 and 11, when compared, suggest that at moderate to low stress levels exposed specimens seem to initiate cracks slightly earlier than do unexposed specimens. Table 4, which contains data obtained on exposed and unexposed specimens at room temperature and at 550 F clearly indicates that the 1000-hour exposure of AM-350 alloy did not measurably affect the rate of crack propagation. The conclusion appears to be that 1000 hours of 550 F exposure at a stress of 40 ksi on the net section has not affected fatigue-crack propagation very substantially.

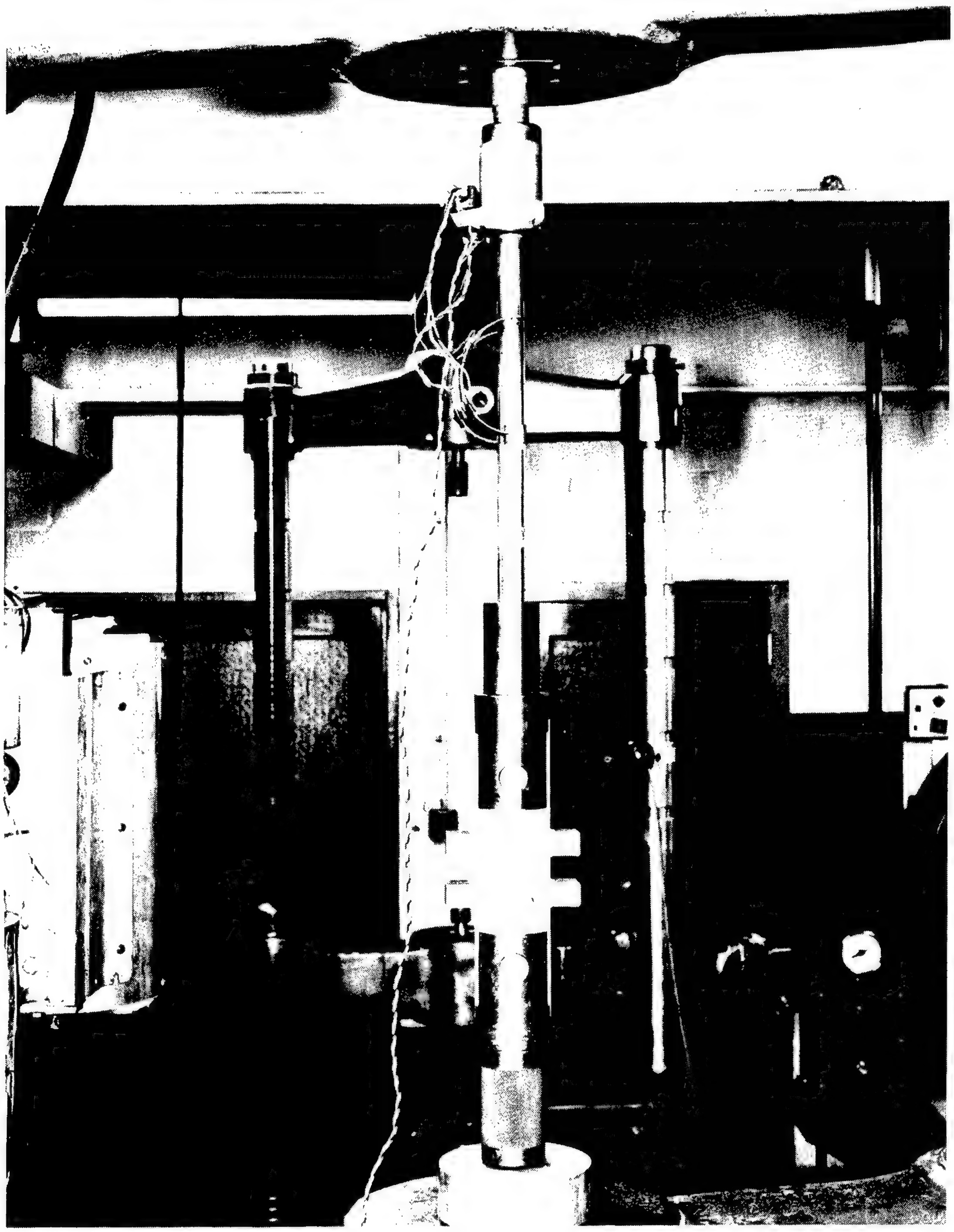
Residual-Static-Strength Studies

Procedures and Equipment

Center-cracked sheet specimens of AM 350 were tested in tension to determine the residual static strength and its dependence upon several variables. Although presented at the beginning of this section, a restatement of the variables seems in order: crack length, test temperature, orientation with respect to the rolling direction, exposure to stress at 550 F, and the fatigue conditions employed to introduce the crack. In this work, attempts also were made to evaluate the fracture toughness parameters, K_{Ic} and K_c using a compliance gage similar to that described by Boyle[6].

In conducting the tension tests, a constant head speed of approximately 0.02 inch/ minute was used. Low-temperature tests were conducted in a mixture of dry ice and alcohol with the specimen completely immersed. Tests at 550 F were conducted in a cylindrical furnace that completely enclosed the specimen. Test temperatures were measured by thermocouples making contact with the specimen near the center crack.

A compliance gage was used to measure elongation across the center crack as a function of the applied load, as shown in Figure 12. Elongation is measured between two points located 2/3 inch above and below the center crack and centered with respect



N98455

FIGURE 12. COMPLIANCE GAGE ATTACHED TO PRECRACKED SHEET SPECIMEN

to the width. The elongation is transmitted by a rod-and-tube arrangement to two beryllium-copper loops, to which electrical-resistance strain gages are attached. These remote gages make it possible to use the compliance gage at temperatures other than ambient. The four strain gages are connected as a full bridge through an SR-4 converter to the recording drum of a hydraulic testing machine. The purpose of using the compliance gage is to determine the load at which the crack first begins to grow or "pop in" (required for K_{Ic} calculations), and the crack length at the onset of rapid crack propagation (required for K_c calculations). In general, fracture-toughness analysis proved to be unwarranted for these materials because (1) no crack "pop in" was detected in any of the tests, and (2) the specimens underwent yielding across the entire net-section prior to appreciable growth of the center crack. The latter invalidates the equation for calculating K_c, whose derivation allows for only a small plastic region at the crack tip. While a so-called "stress-intensity factor", K_i, was computed for the point in the test at which the load-elongation curves first deviated from a straight line (indicating a change in compliance) the value may or may not be equal to K_{Ic}. Because of the questionable status of this factor, values have not been included in this report although they can be made available.

The results of room-temperature tensile tests on center-cracked AM-350 sheet specimens are presented in Table 5. The data have been grouped and labeled A,B,C, etc., to facilitate comparison; as a result, some specimens are listed more than once. As examination of Table 5 will show, the results on AM-350 are encouraging with respect to possible use of this material in a supersonic transport. AM-350 appears to maintain a high percentage of its strength even in the presence of long cracks and is virtually unaffected by 1000-hour exposure to stress at 550 F. Furthermore, the residual strength is virtually independent of the manner in which cracks originate.

Effect of Crack Length

(See Groups A, B, C, I, J, K, L, Table 5)

Three different crack lengths (3/16, 3/8, and 3/4 inch) were investigated. The effect of crack length on residual static strength is shown in Figure 13, where the ratio of residual strength to ultimate strength, σ_R/σ_u, is plotted as a function of crack length over specimen width ℓ/W. The broken line indicates the curve that would be obtained if the only effect of the crack were to reduce the cross-sectional area. It is apparent that all the crack lengths investigated have a detrimental effect on strength; however, the impairment of strength is much less than that reported for AM-355 and PH 15-7 Mo at comparable strength levels by Christensen and Denke[7]. Some of their data for 2-inch-wide, 50-mil-thick specimens are included in Figure 13 for comparison.

Effect of Orientation With Respect to the Rolling Direction

(Compare Groups A and C, Table 5)

The major portion of this investigation was concerned with specimens oriented with their rolling direction parallel to the applied tension stress. However, several

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TABLE 5. RESULTS OF TENSILE TESTS ON CENTER-CRACKED AM 350 SHEET SPECIMENS

Specimen	Orientation	Crack Length, inches	Fatigue Stress Amplitude	Fatigue Temperature, F	Cyclic Speed, cpm	Exposure Time, hours	Test Temperature, F	σ_N[a], ksi	σ_R[b], ksi
A 6310	L	0.188	Medium[c]	75	1200	--	75	217.5	197.1
6313	L	0.375	Medium[c]	75	1200	--	75	216.0	175.5
6317	L	0.751	Medium[c]	75	1200	--	75	214.1	133.7
B 834	L	0.188	Medium[c]	75	1200	1000	75	(d)	(d)
831	L	0.186	Medium[c]	75	1200	1000	75	218.4	198.0
8320	L	0.375	Medium[c]	75	1200	1000	75	220.8	179.4
8311	L	0.747	Medium[c]	75	1200	1000	75	214.4	134.3
C 8321	T	0.188	Medium[c]	75	1200	--	75	205.6	186.3
6321	T	0.383	Medium[c]	75	1200	--	75	199.5	161.3
7322	T	0.751	Medium[c]	75	1200	--	75	195.1	121.9
D 732	L	0.753	Medium[c]	-110	1200	--	75	209.9	130.9
7310	L	0.754	Medium[c]	-110	1200	--	75	211.6	131.9
6317	L	0.751	Medium[c]	75	1200	--	75	214.1	133.7
738	L	0.744	Medium[c]	550	1200	--	75	214.0	134.4
833	L	1.009	Medium[c]	550	1200	1000	75	209.7	103.9
E 836	L	0.757	High[e]	75	1200	--	75	212.7	132.2
733	L	0.763	High[e]	75	1200	--	75	211.6	130.9
735	L	0.748	High[e]	75	120	--	75	208.3	130.4
7315	L	0.757	High[e]	75	34	--	75	215.3	133.8
F 736	L	0.746	High[e]	75	1200	1000	75	217.4	136.3
7319	L	0.766	High[e]	75	120	1000	75	216.9	133.8
8310	L	0.749	High[e]	75	34	1000	75	216.3	135.3
G 7311	L	0.749	Low[f]	75	1200	--	75	212.5	132.9
6317	L	0.751	Medium[d]	75	1200	--	75	214.1	133.7
836	L	0.757	High[e]	75	1200	--	75	212.7	132.2

TABLE 5. (Continued)

Specimen	Orientation	Crack Length, inches	Fatigue Stress Amplitude	Fatigue Temperature, F	Cyclic Speed, cpm	Exposure Time, hours	Test Temperature, F	σ_N(a), ksi	σ_R(b), ksi
H 837	L	0.767	Low(f)	75	1200	1000	75	213.1	131.4
8311	L	0.747	Medium(c)	75	1200	1000	75	214.4	134.3
736	L	0.746	High(e)	75	1200	1000	75	217.4	136.3
I 638	L	0.181	Medium(c)	75	1200	--	550	(d)	(d)
6312	L	0.373	Medium(c)	75	1200	--	550	174.7	142.2
8319	L	0.753	Medium(c)	75	1200	--	550	168.2	104.9
J 8316	L	0.189	Medium(c)	75	1200	1000	550		(d)
835	L	0.375	Medium(c)	75	1200	1000	550	168.9	137.3
8313	L	0.758	Medium(c)	75	1200	1000	550	159.5	99.0
K 634	L	0.183	Medium(c)	75	1200	--	-110		(d)
6311	L	0.375	Medium(c)	75	1200	--	-110	215.4	175.0
6316	L	0.752	Medium(c)	75	1200	--	-110	209.0	130.4
L 832	L	0.190	Medium(c)	75	1200	1000	-110	(d)	(d)
7317	L	0.374	Medium(c)	75	1200	1000	-110	218.9	177.9
8317	L	0.749	Medium(c)	75	1200	1000	-110	212.8	133.1

(a) σ_N = net-section strength = $\dfrac{\text{maximum load}}{\text{(width-crack length) x thickness}}$.

(b) σ_R = residual strength = $\dfrac{\text{maximum load}}{\text{width x thickness}}$.

(c) Medium stress amplitude = 40,000 psi mean stress plus 30,000 psi alternating stress.
(d) Specimen failed in grips.
(e) High stress amplitude = 40,000 psi mean stress plus 55,000 psi alternating stress.
(f) Low stress amplitude = 40,000 psi mean stress plus 15,000 alternating stress.

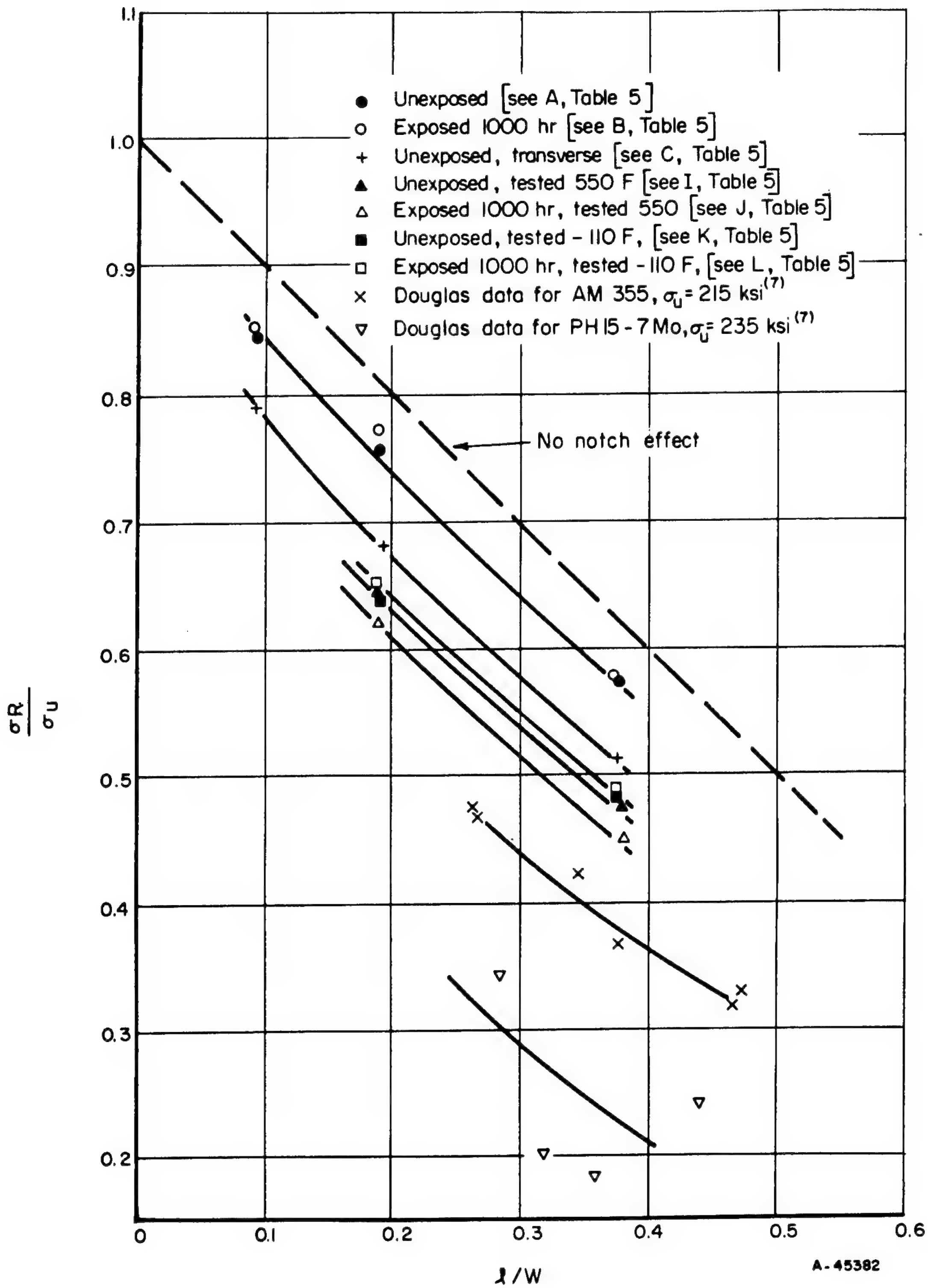

FIGURE 13. EFFECT OF CRACK LENGTH ON THE RATIO AT RESIDUAL STRENGTH TO ULTIMATE STRENGTH FOR 50-MIL-THICK 2-INCH-WIDE SHEET SPECIMENS

tests were conducted on transverse specimens to determine whether orientation has a marked effect on crack sensitivity. As shown in Figure 13, the limited tests show that transverse specimens are weakened to a greater extent by cracks than are longitudinal specimens.

Effect of 1000-Hour Exposure to Stress at 550 F

(Compare Groups A and B, E and F, G and H, I and J, K and L, Table 5.)

During this first year's program, center-notched AM-350 specimens were exposed in air to a net-section stress of 40,000 psi at 550 F for 1000 hours, prior to introducing fatigue cracks. Additional specimens are being exposed for longer times, up to 10,000 hours, and will be examined in a continuation of the program.

Examination of Table 5 and Figure 13 reveals that exposure to a stress of 40,000 psi at 550 F for 1000 hours prior to fatigue cracking has very little effect on the residual strength of AM-350. Although slight effects of exposure may be noted in comparing some of the data, the effects do not appear to be important with regard to the intended application of this material. Whether or not the same can be said for longer exposure times must await planned future experiments.

Effect of Test Temperatures

(Compare Groups A, I, and K, and Groups B, J, and L, Table 5.)

Residual-strength experiments were conducted on AM-350 at room temperature, -110 F, and 550 F to determine crack sensitivity in the probable temperature range of application.

Referring to Figure 13, it is seen that AM-350 center-cracked specimens are weakened to a greater extent at both -110 and 550 F than they are at room temperature. This agrees with the findings of Espey, Bubsey, and Brown[8] on edge-notched specimens of the same steel. If, instead of looking at σ_R/σ_u ratios, one looks at residual-strength values (see Table 5), it is apparent that much lower strengths are obtained at 550 F than at -110 F for a given crack length. In fact, the residual strengths are approximately the same at room temperature and at -110 F.

Effect of Fatigue Conditions Used to Introduce Cracks

To determine whether or not the residual strength of fatigue-cracked AM-350 is influenced by the manner in which the crack is introduced, experiments were performed in which the fatigue-stress amplitude, fatigue temperature, and cycling speed were varied.

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Effect of Fatigue-Stress Amplitude. (See Groups G and H, Table 5.)

Three different fatigue-stress amplitudes were used to introduce 3/4-inch cracks in AM-350. These were: 15,000 psi (low), 30,000 psi (medium), and 55,000 psi (high), all superimposed upon a mean stress of 40,000 psi. As reference to Table 5 reveals, varying the fatigue-stress amplitude has virtually no effect on residual strength.

Effect of Fatigue Temperature. (See Group D, Table 5.)

Three different fatigue temperatures, namely room temperature, -110 and 550 F, were employed to introduce 3/4-inch fatigue cracks in AM-350 sheet specimens. No appreciable effect of fatigue temperature on residual strength was observed, despite the fact that the fatigue cracks produced at 550 F differed markedly in appearance from those produced at room temperature and -110 F. The fatigue cracks produced at 550 F were inclined at 45 degrees to the tensile axis, whereas the cracks produced at room temperature and at -110 F were flat and perpendicular to the tensile axis.

Effect of Cyclic Speed. (See Groups E and F, Table 5.)

Three different cyclic speeds, 1200, 120, and 34 cycles per minute, were used to introduce 3/4-inch fatigue cracks in AM-350 sheet specimens. No appreciable effect of cyclic speed upon residual strength was discernible, as shown in Table 5.

Exposure of Precracked Specimens

In studying the effect of exposure on fatigue-crack propagation and residual strength of AM-350 steel, all specimens were cracked after exposure. However, it also appeared to be of interest to determine the effect of exposure on specimens cracked prior to exposure, inasmuch as Christensen and Denke[7] had observed slight crack extension during exposure to stress at elevated temperature. Accordingly, two AM-350 sheet specimens (one longitudinal and one transverse) containing center cracks were exposed to a stress of 40,000 psi at 550 F. To facilitate detection of slight growth of the crack or plastic deformation at the crack tip, the longitudinal specimen was polished prior to exposure and a grid of microhardness impressions was introduced at one end of the crack. Photomicrographs at 100X magnification showed that the crack did not grow during exposure (at least on the surface) and that no appreciable plastic deformation occurred. Observation after 2000 hours' exposure yielded the same results. Likewise, no change in crack length was detected in the transverse specimen after 2000 hours' exposure. These results indicate that there is little danger of AM-350 undergoing delayed failure at stresses of 40,000 psi at 550 F.

SS, Ti

FATIGUE BEHAVIOR OF AM-350 AND Ti-8Al-1Mo-1V ALLOYS

In this part of the program, the unnotched- and notched-sheet-specimen behavior of the two materials were explored. The selection of variables for study encompassed the stress and the temperature limits to which certain surfaces of the supersonic transport will be exposed. Most of the testing was carried out under mean stress conditions of 40 ksi for the AM-350 and 25 ksi for the Ti-8Al-1Mo-1V alloy. Limited exploration of the effect of mean stress on basic fatigue strength of AM-350 was carried out with experiments at 20-ksi mean stress. The fatigue behavior of both alloys was evaluated at three temperatures: -110 F, room temperature, and 550 F. All specimens for generation of S-N data were taken with the longitudinal axis parallel to the rolling direction.

Base-line data were obtained on specimens having no prior exposure. Other specimens were exposed to temperature and stress prior to fatigue testing. In all cases, exposure temperature was 550 F. For the AM-350 alloy, the exposure stress was 40 ksi and for the titanium alloy, it was 25 ksi. During this first year no experiments on titanium specimens with prior exposure were performed, although specimens have been placed in the exposure chamber. Notched AM-350 specimens with 1000 hours' exposure were fatigue tested at -110 F and at 550 F; a few with 3000 hours' prior exposure were tested at -110 F. The detailed stress-lifetime data are listed in Appendix B.

S-N curves that illustrate the behavior of the two alloys are shown in Figures 14 through 21. Some curves are duplicated in several figures in order to facilitate comparisons. In general each figure speaks for itself; however, certain comments appear necessary for some:

(1) Figures 16 and 17 in combination show the effect of temperature on the fatigue strength of unnotched and notched AM-350 alloy. At a mean stress level of 40 ksi, fatigue limits decrease as the test temperature increases, much in accordance with tensile strength. Notched behavior at lifetimes in excess of 40,000 cycles is such that room-temperature strength is lowest; that at -110 F remains the highest.

(2) The effects of prior exposure of AM-350 alloy notched specimens on their fatigue lifetimes at -110 F and at 550 F are shown in Figures 18 and 19, respectively. Although there is an apparent slight reduction in lifetime of all specimens exposed for 1000 and 3000 hours and tested at -110 F, the effect is small and possibly questionable. At 550 F, where specimens with prior exposures of 1000 hours only were tested, there is no significant difference between lifetimes of exposed and unexposed specimens.

Table 6 has been prepared from the S-N curves in a number of these figures. The table presents K_f values obtained for each material at given lifetimes and for each material at given lifetimes and for each of the three test temperatures. In this report, K_f has been defined as the ratio of the maximum test stresses (unnotched to notched) at the same mean stress and lifetime.

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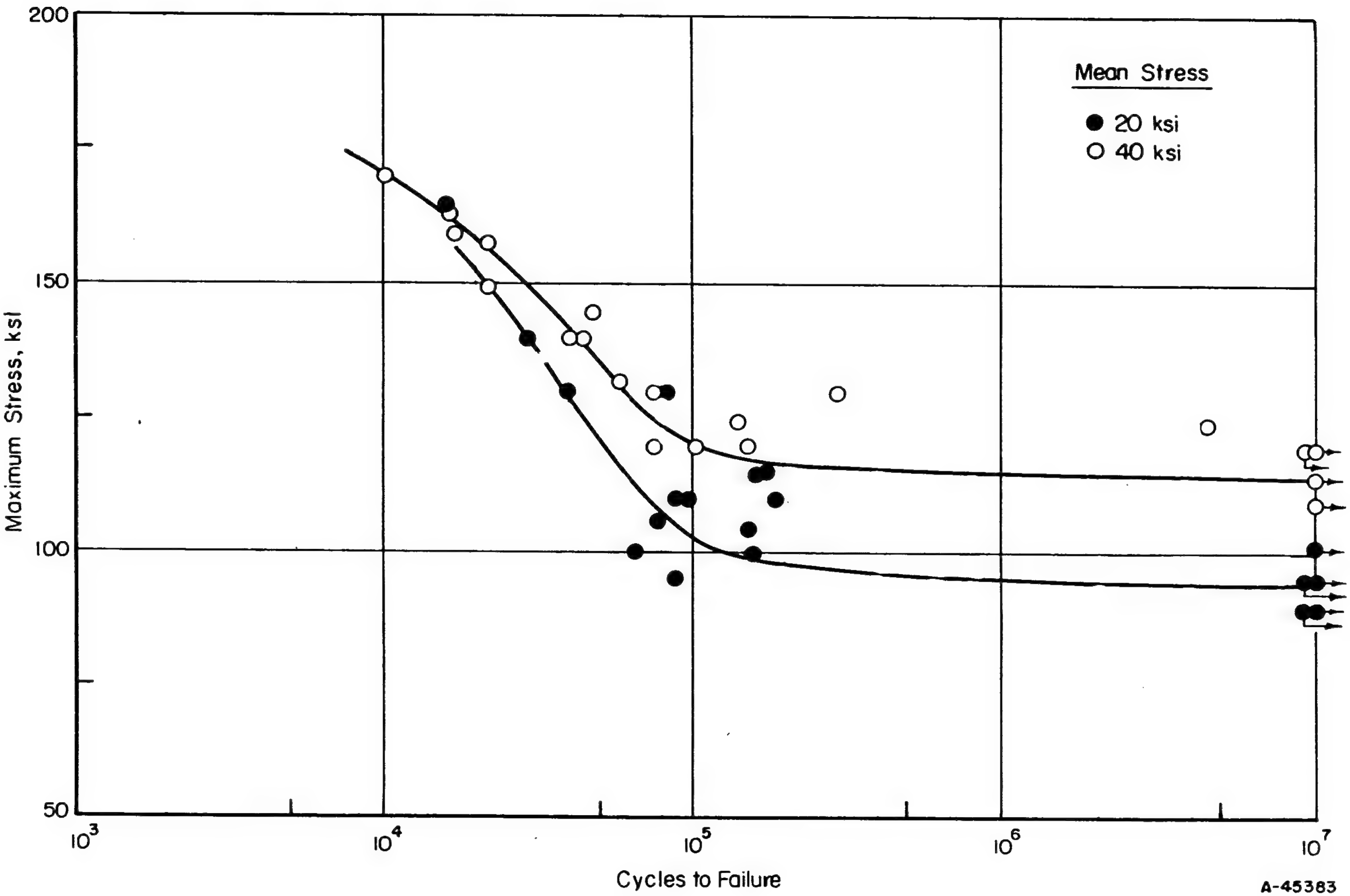

FIGURE 14. FATIGUE BEHAVIOR OF UNNOTCHED AM-350 STEEL SPECIMENS AT ROOM TEMPERATURE

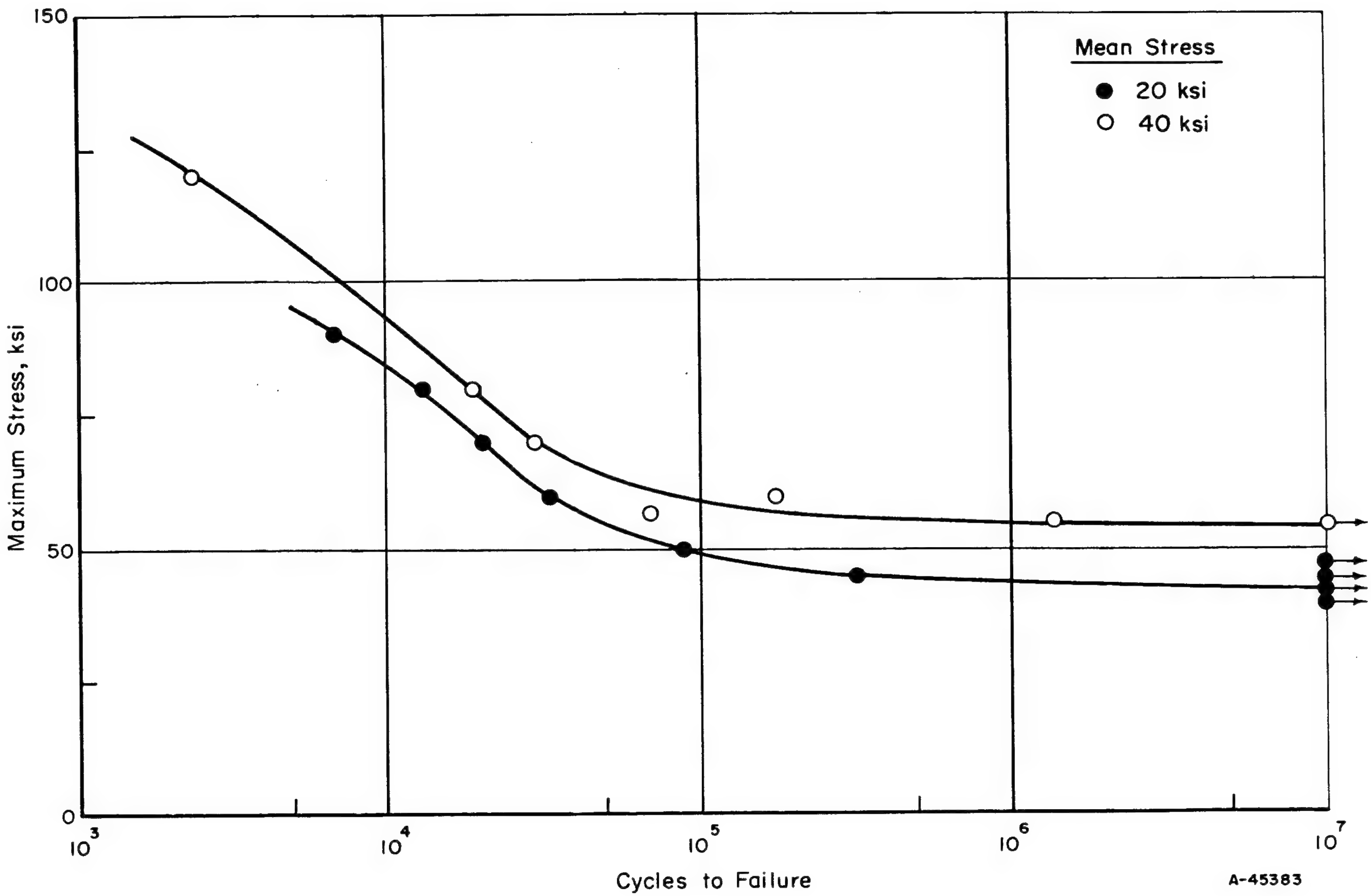

FIGURE 15. FATIGUE BEHAVIOR OF NOTCHED (K_t = 4.0) AM-350 SPECIMENS AT ROOM TEMPERATURE

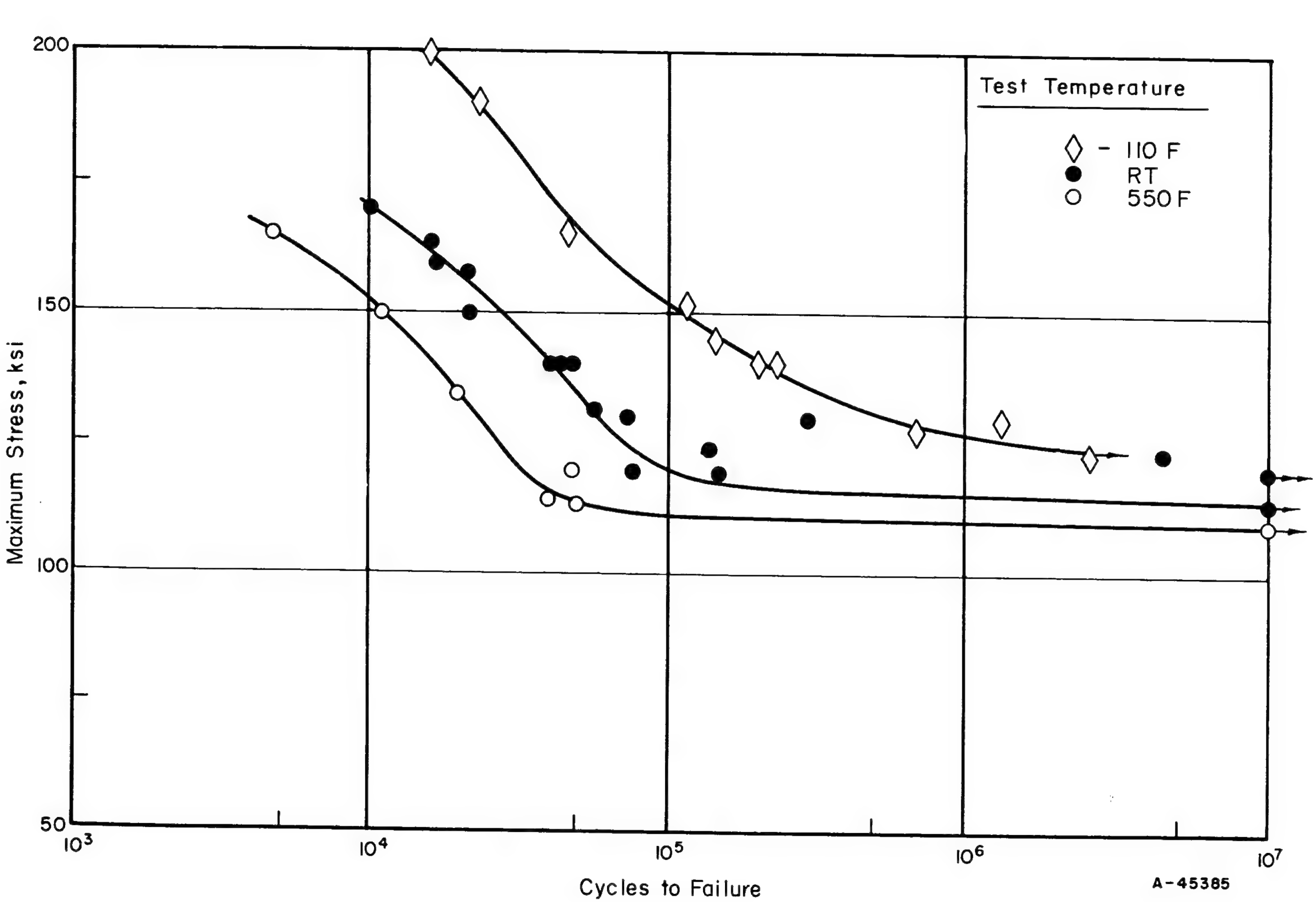

FIGURE 16. FATIGUE BEHAVIOR OF UNNOTCHED AM-350 STEEL SPECIMENS AT 40-KSI MEAN STRESS

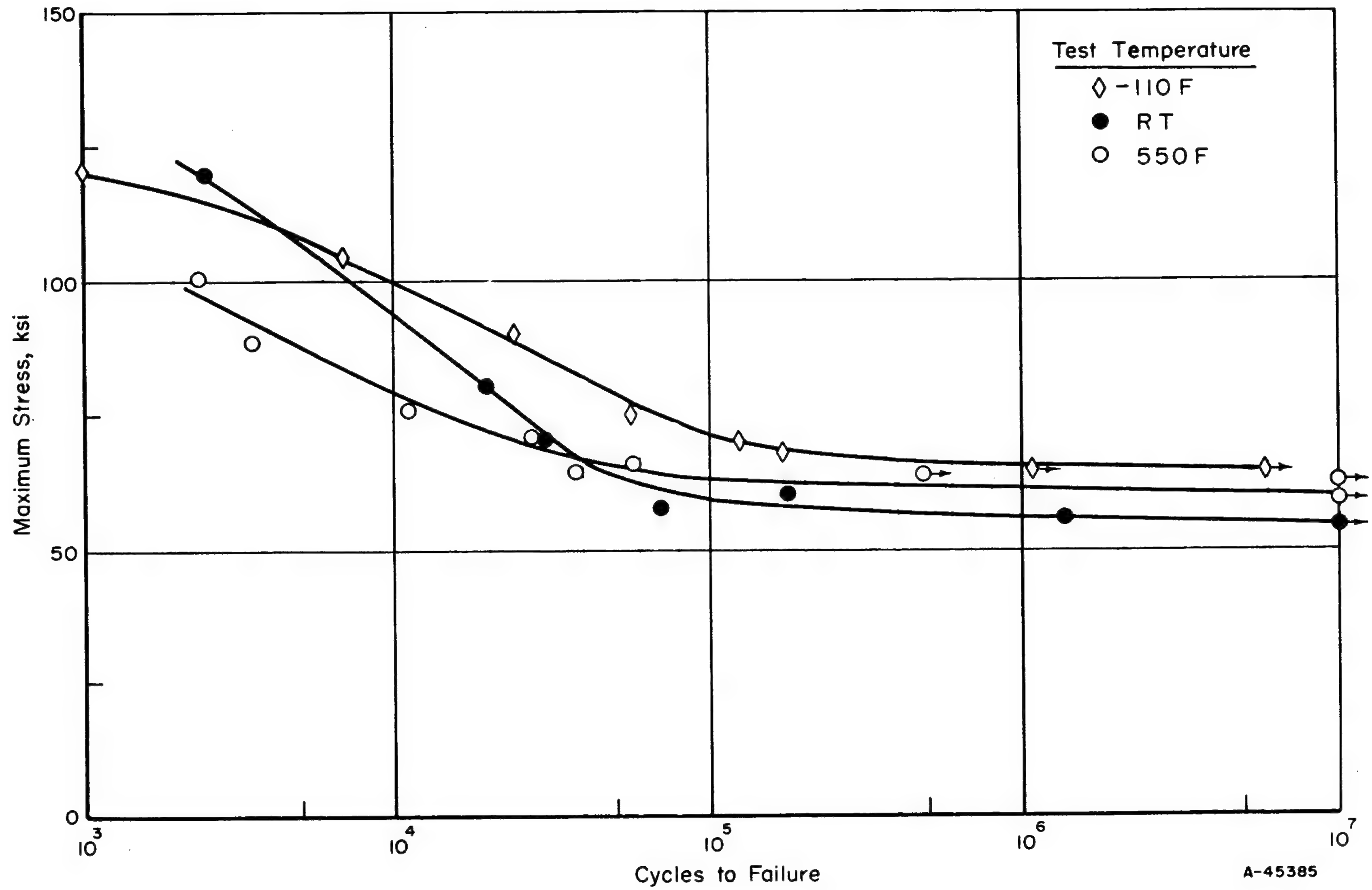

FIGURE 17. FATIGUE BEHAVIOR OF NOTCHED (K_t = 4.0) AM-350 STEEL AT 40-KSI MEAN STRESS

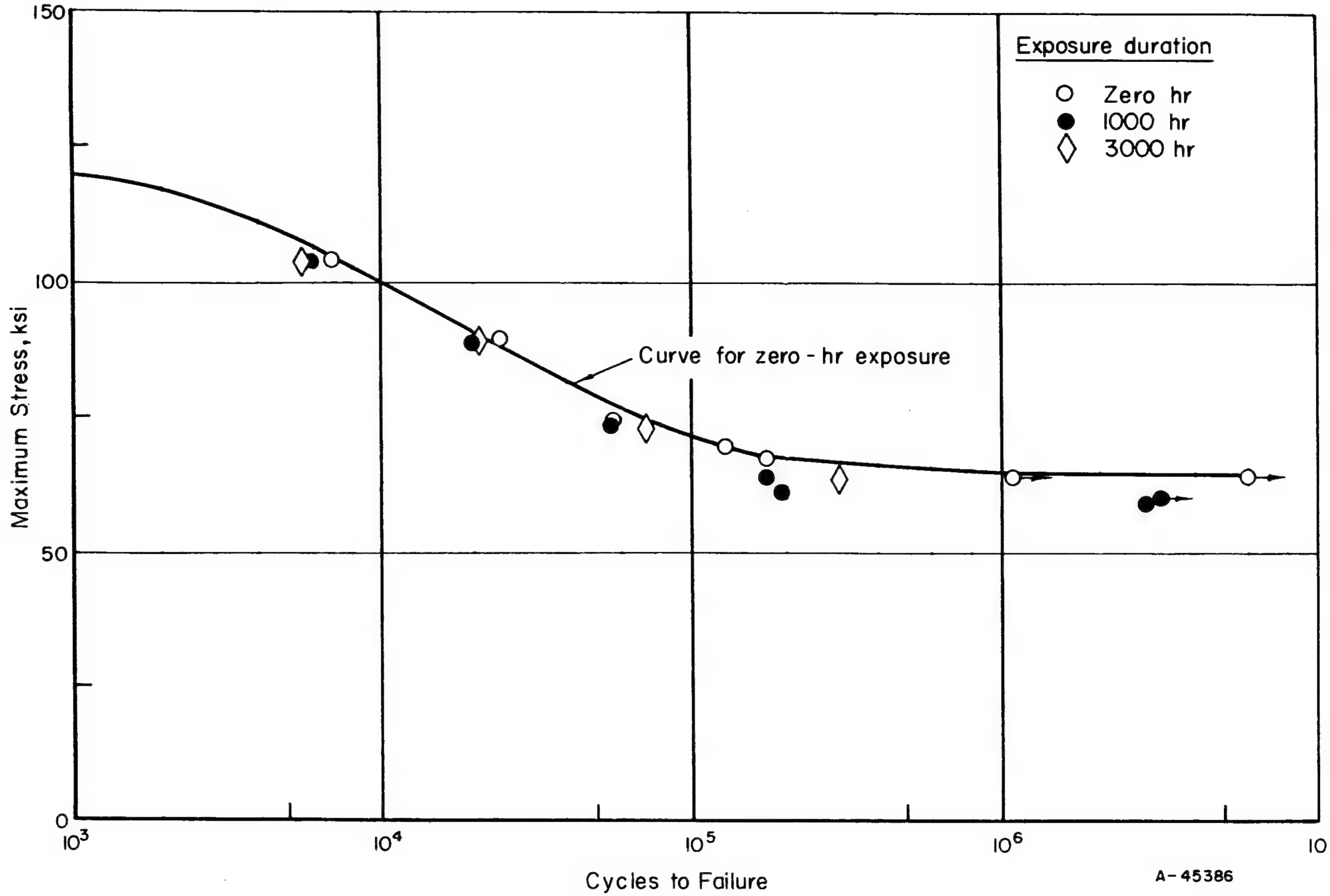

FIGURE 18. EFFECT OF PRIOR EXPOSURE ON THE FATIGUE BEHAVIOR OF NOTCHED (K_t = 4.0) AM-350 STEEL AT -110°F AND 40-KSI MEAN STRESS

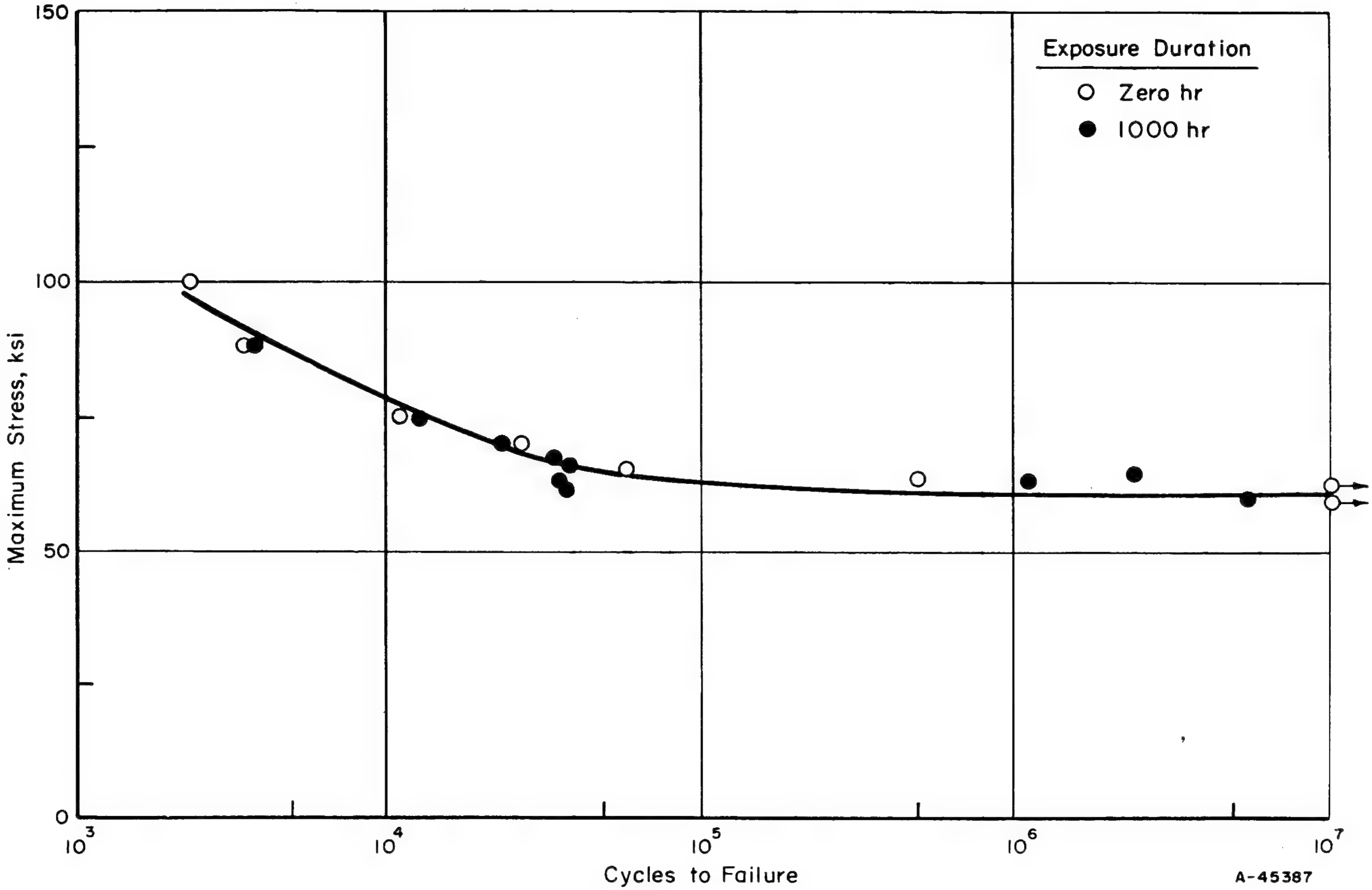

FIGURE 19. EFFECT OF PRIOR EXPOSURE ON THE FATIGUE BEHAVIOR OF NOTCHED ($K_t = 4.0$) AM-350 STEEL AT 550 F AND 40-KSI MEAN STRESS

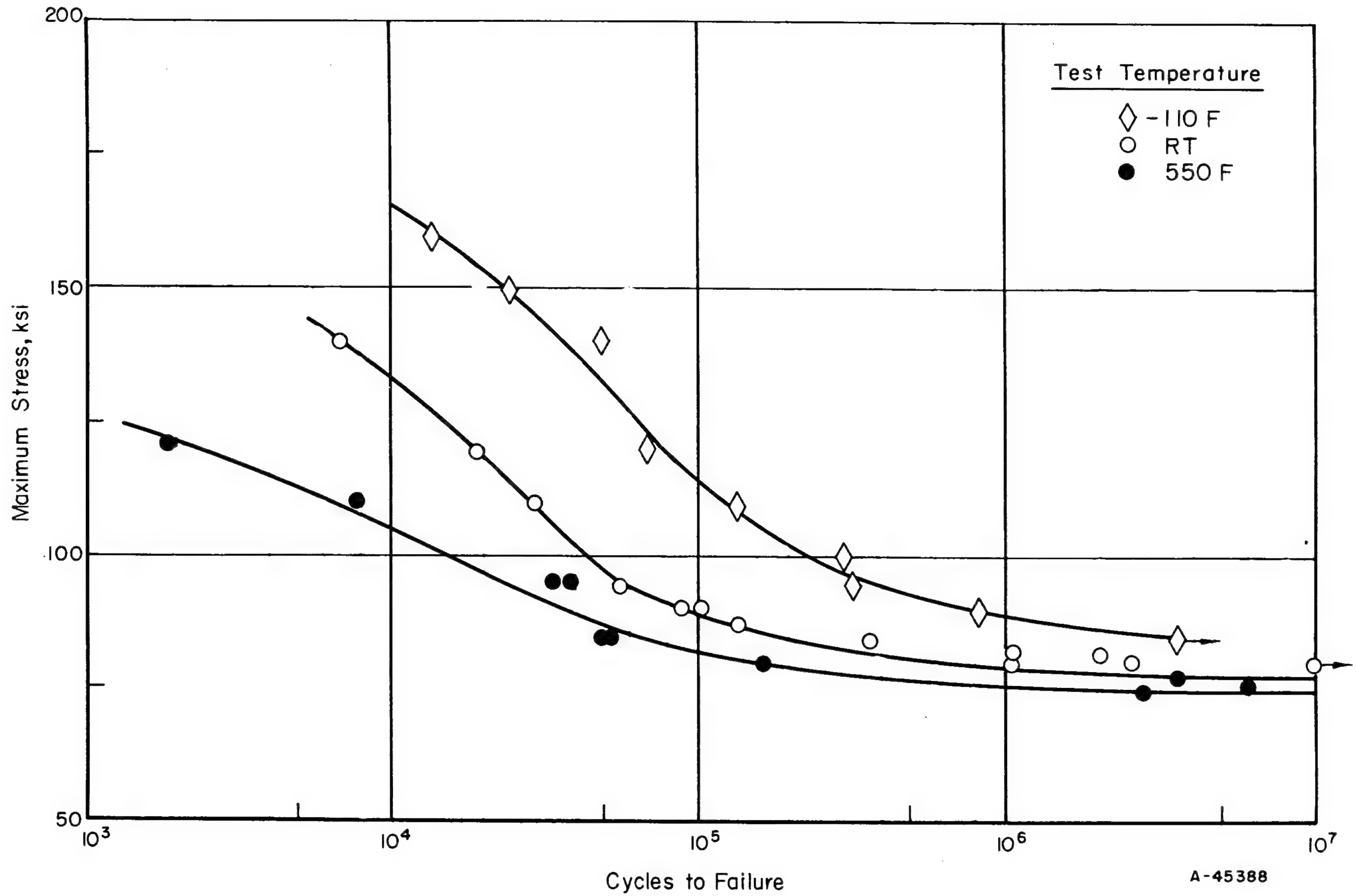

FIGURE 20. FATIGUE BEHAVIOR OF UNNOTCHED 8Al-1Mo-1V TITANIUM ALLOY SPECIMENS AT 25-KSI MEAN STRESS

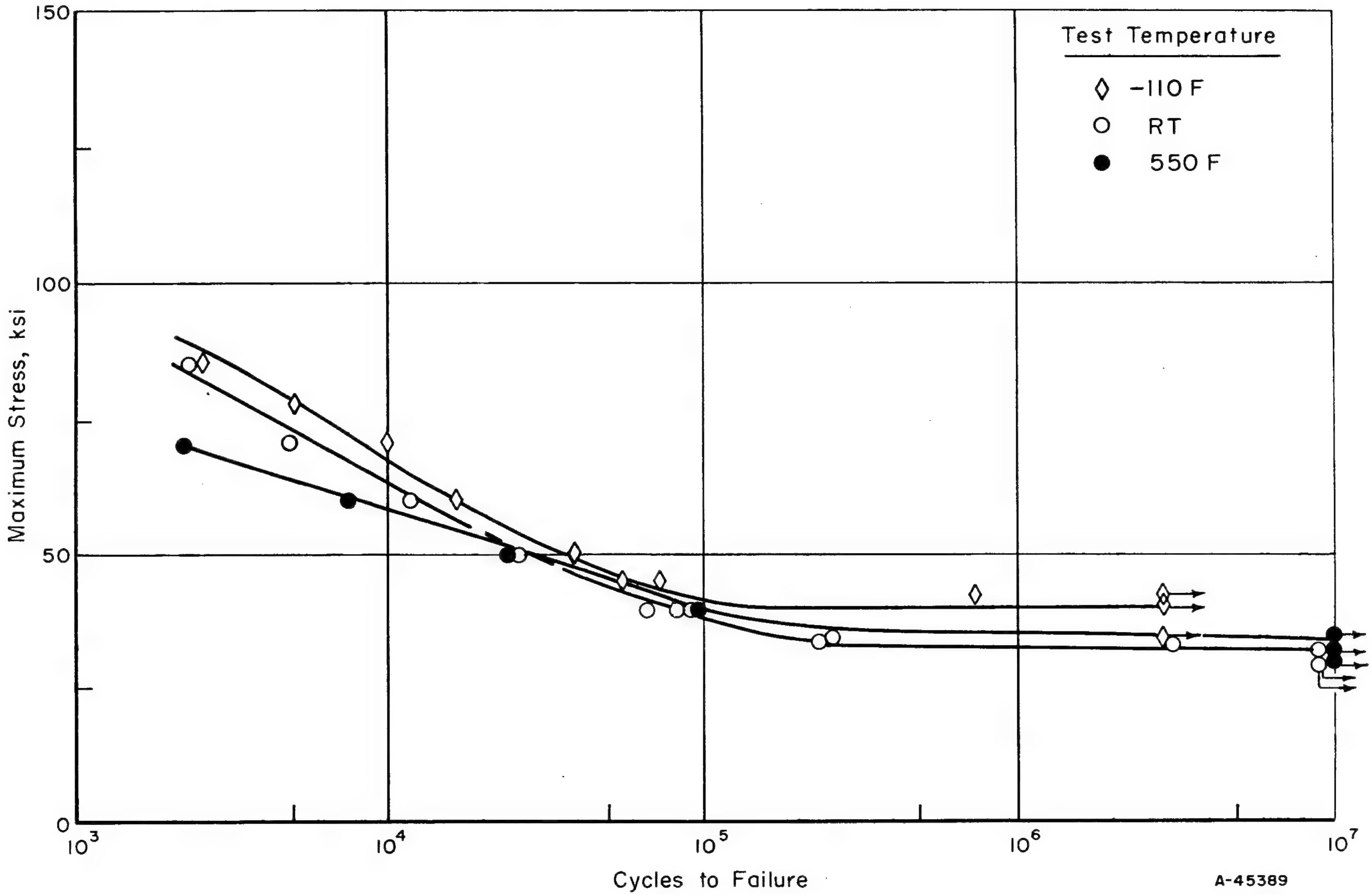

FIGURE 21. FATIGUE BEHAVIOR OF NOTCHED (K_t = 4.0) TITANIUM ALLOY SPECIMENS AT 25-KSI MEAN STRESS

TABLE 6. FATIGUE NOTCH FACTORS FOR THREE TEMPERATURES FOR EDGE-NOTCHED SPECIMENS WITH $K_t = 4.0$

Lifetime, cycles	K_f -110 F	K_f RT	K_f 550 F
	Ti-8Al-1Mo-1V at 25-Ksi Mean Stress		
1×10^4	2.4	2.2	1.8
4×10^4	2.8	2.2	1.9
1×10^5	2.8	2.2	2.2
4×10^5	2.2	2.3	2.3
1×10^6	2.2	2.3	2.4
4×10^6	2.1	2.2	2.3
1×10^7	--	2.2	2.3
	AM-350 at 40-Ksi Mean Stress		
1×10^4	--	1.8	1.9
4×10^4	2.1	2.1	1.7
1×10^5	2.1	2.0	1.8
4×10^5	2.0	2.0	1.8
1×10^6	1.9	2.0	1.8
4×10^6	--	2.1	1.8
1×10^7	--	2.1	1.8

From the table it is seen that for the titanium alloy K_f values are nearly constant for lifetimes in excess of 10^5 cycles. K_f values are almost independent of temperature in this lifetime range (there is a slight tendency for lower values of K_f at low temperatures). About the same statements can be made for the AM-350 alloy; however, the slightly lower values are associated with the data obtained at 550 F. Comparison of the two alloys indicates K_f values for steel to be slightly lower than comparable values for the titanium alloy.

To provide some better insight into how these values compare with those of materials commonly used for aircraft structure the following tabulation has been prepared[1,9]:

Lifetime, cycles	K_f Values for Indicated Material	
	2024-T3	7075-T6
10^4	2.3	2.7
4×10^4	2.4	2.8
10^5	2.6	2.7
10^7	1.9	2.7

In computing the above results, the same definition of K_f was used and the notch was geometrically similar with a $K_t = 4.0$. Also, the mean stress was selected so that the ratio of mean stress to ultimate strength for the two aluminum alloys was about the same as the ratios for the titanium and steel alloys.

SS, Ti

FRACTOGRAPHIC EXAMINATION OF FATIGUE FRACTURES AND TENSILE FRACTURE

SS, Ti

Unexposed AM-350 steel specimens with central notches were fatigue cracked at three different alternating stress levels, i.e., 15,000, 30,000, and 55,000 psi, superimposed upon a mean stress of 40,000 psi. The total crack length (tip to tip) as a function of the number of cycles is shown in Figure 22; the discontinuities in the curves reflect load readjustments to keep the net-section stress within ± 10 per cent of the indicated values.

Replicas for examination in the electron microscope were taken from the fatigue-crack surfaces at the positions indicated by the arrows in Figure 22. Electron micrographs of some of the areas examined are shown in Figures 23 and 24. Note the striations in the surface, typical of fatigue failures in a wide variety of metals. These striations were detected across the entire thickness of the specimens; no evidence of shear lips was found. Other interesting observations concerning the fracture-surface

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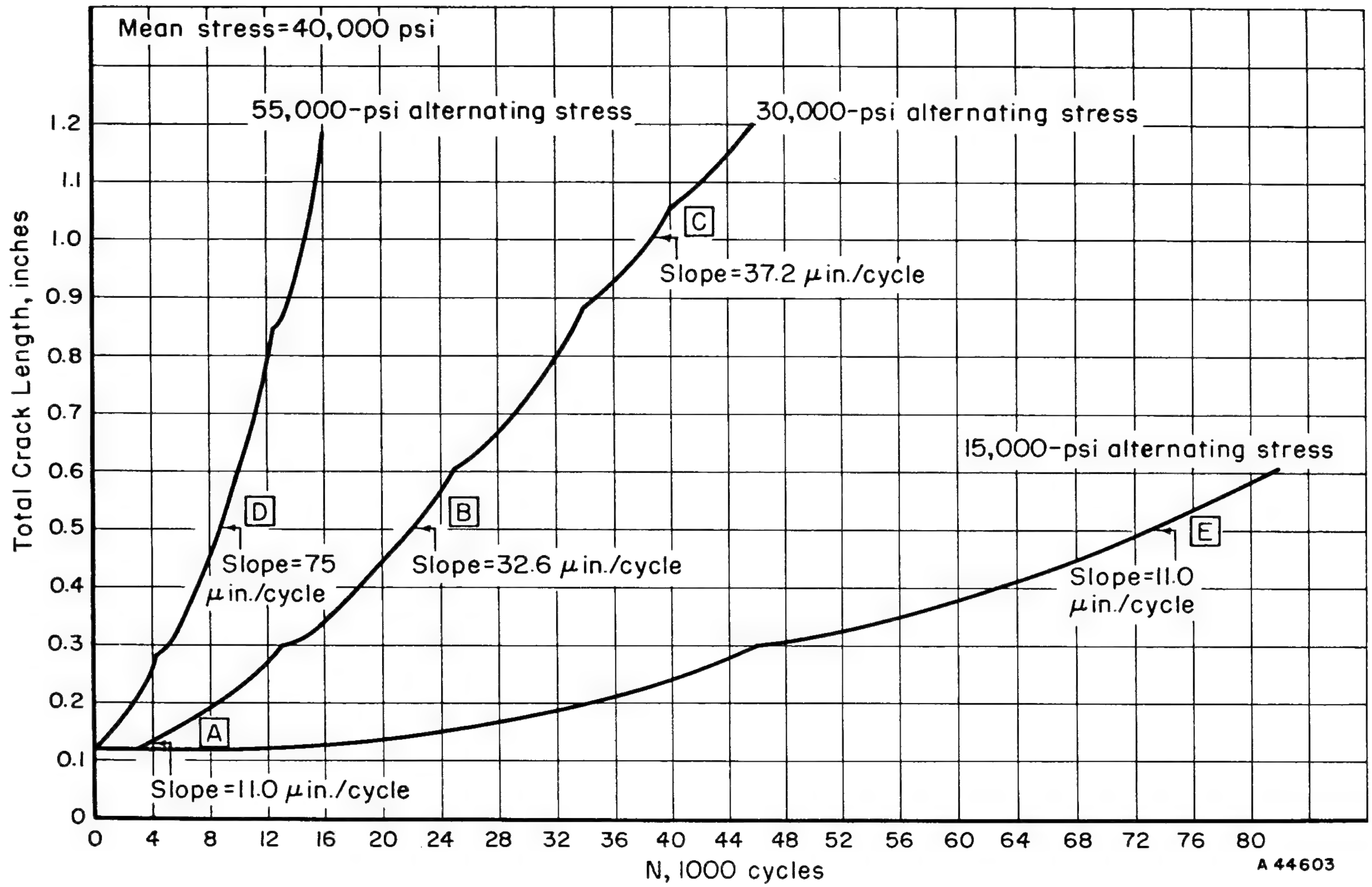
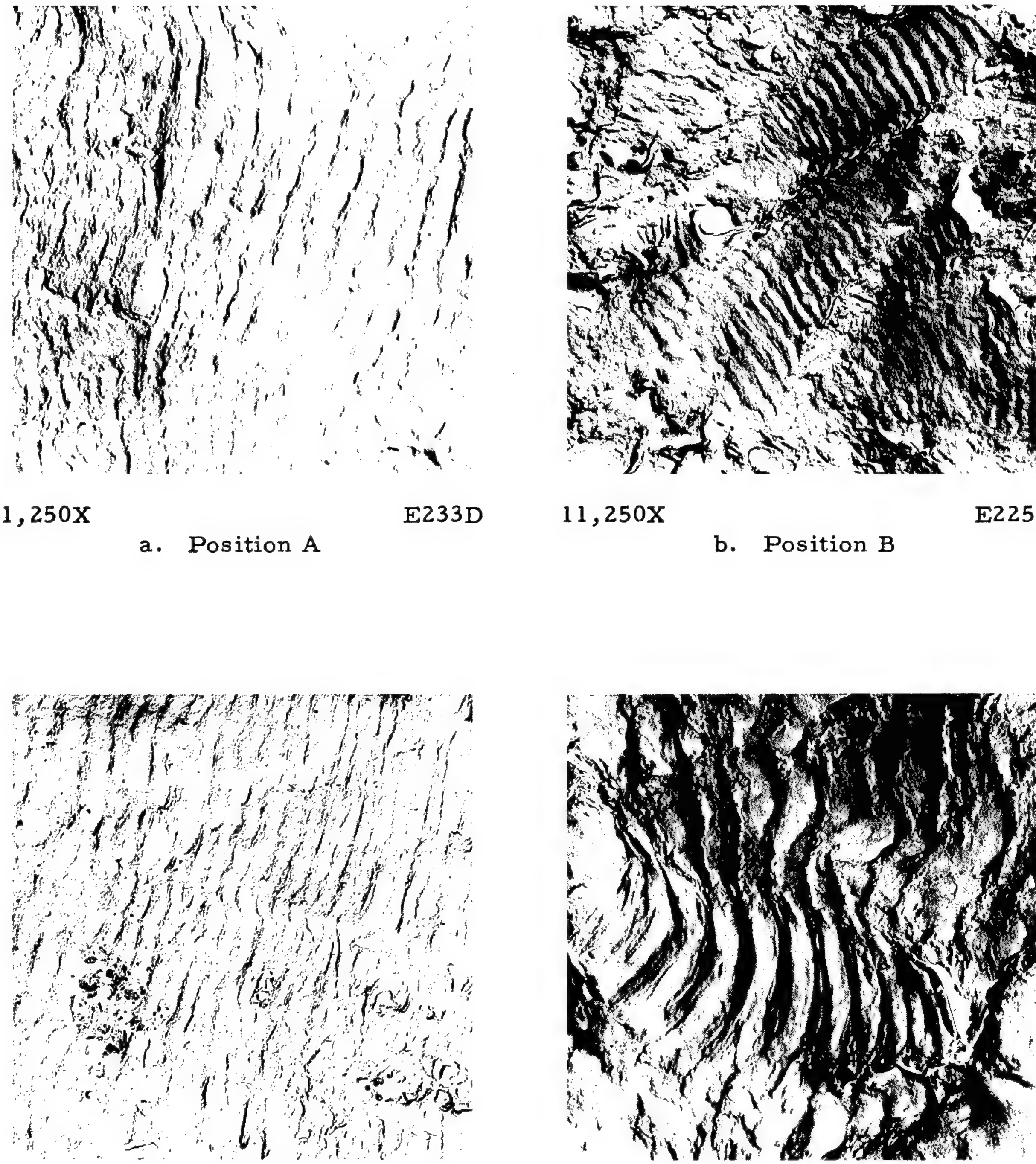


FIGURE 22. FATIGUE CRACK PROPAGATION CURVES FOR AM-350 STEEL SHEET SPECIMENS, 2 INCHES WIDE BY 0.051 INCHES THICK

Stresses were maintained within ±10% of the values indicated; the discontinuities in the curves are the result of load readjustments.



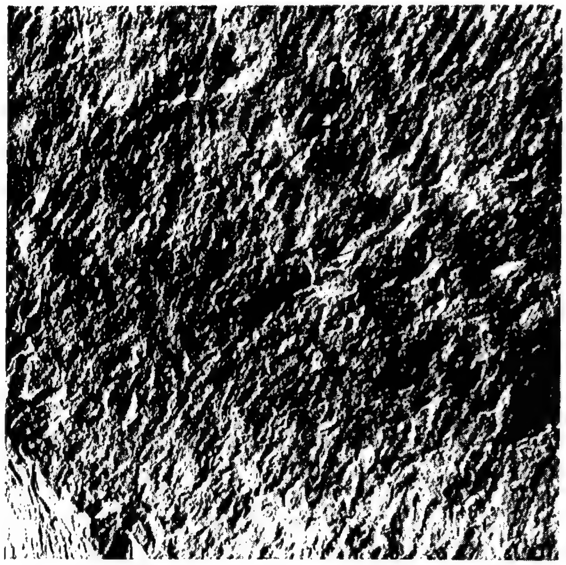
11,250X E233D
a. Position A

11,250X E225B
b. Position B

11,250X E226E
c. Position C

11,250X E225E
d. Position B

FIGURE 23. ELECTRON MICROGRAPHS OF REPLICAS OF AM 350 FATIGUE FRACTURE SURFACES, TESTED AT 40-KSI MEAN STRESS AND 30-KSI ALTERNATING STRESS

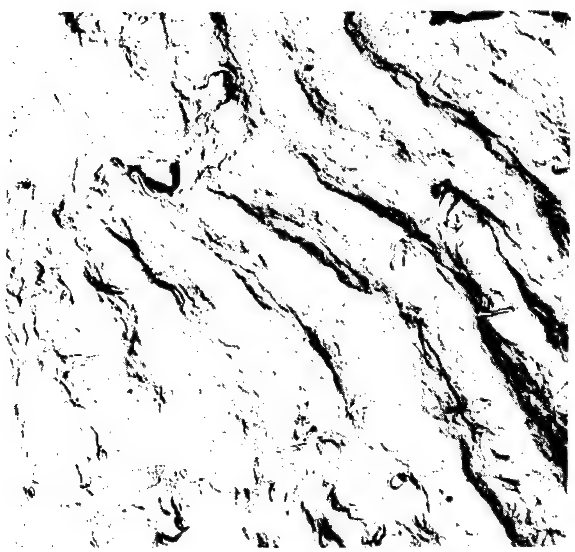


11,250X E224C

a. Position E

11,250X E224E

b. Position E



11,250X E233C

c. Position D

FIGURE 24. ELECTRON MICROGRAPHS OF REPLICAS OF AM 350 FATIGUE FRACTURE SURFACES, (a) AND (b) TESTED AT 40-KSI MEAN STRESS AND 15-KSI ALTERNATING STRESS, AND (c) TESTED AT 40-KSI MEAN STRESS AND 55-KSI ALTERNATING STRESS

appearance include

(1) The striations generally proceed directly away from the crack origin; however, they sometimes curve and move at an angle to the over-all direction of crack propagation for short distances.

(2) Areas exhibiting striations are frequently surrounded by areas of relatively flat fracture in which no striations are apparent. (see Figures 23b and 24b).

(3) The striation spacing is not uniform in a given specimen; it frequently varies by a factor of 3 or more in closely adjacent regions of the fatigue surface.

(4) Major striations are sometimes observed to consist of a number of minor striations, (see Figure 23d).

(5) The striation spacing frequently is decreased in the vicinity of inclusions.

These observations suggest that fatigue-crack growth in AM-350 steel is not as smooth and continuous as indicated by the curves of Figure 22.

To examine the relationship between the number of cycles and the number of striations, the crack-propagation rates (μin./cycle) shown in Figure 24 were compared with the striation spacings (μin./striation) obtained from electron micrographs. Dividing the crack-propagation rate by the striation spacing gives the number of striations per fatigue cycle. The results are as follows:

Location	Striations/Cycle
A	0.3 to 1.0
B	0.7 to 2.1
C	0.8 to 3.5
D	0.9 to 4.5
E	0.9 to 2.3

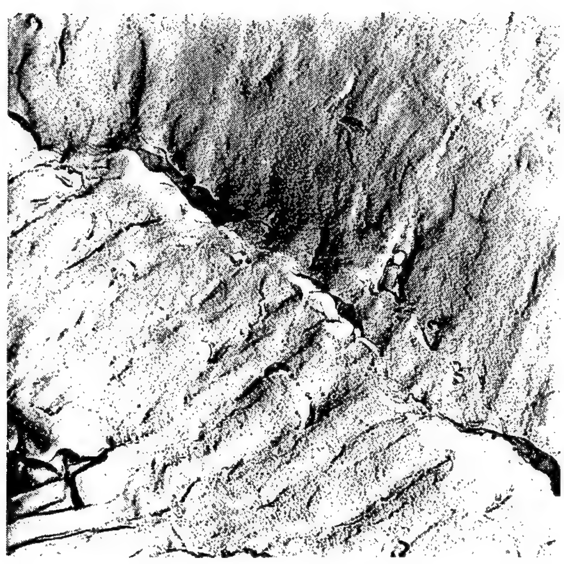
These results are compatible with the suggestion of others[10,11] that each striation represents one fatigue cycle.

Replicas also were made of a fatigue-cracked surface produced at 550 F; as mentioned previously, fatigue cracks produced at 550 F were inclined at 45 degrees to the tensile axis, except near the crack origin, where they were normal to the tensile axis. Electron micrographs taken in each of these areas are shown in Figure 25. As was observed in fatigue cracks produced at room temperature, striations are present on the surface; these are more closely spaced near the origin where the crack-propagation rate is low (Figure 25a) than they are further away from the origin, where the crack-propagation rate is higher (Figure 25b). This is similar to the appearance of cracks produced at room temperature.

Fracture surfaces of a specimen fatigued at room temperature and then tested in tension at room temperature were also replicated and examined with the electron

11,250X E269E

a. Near Crack Origin



11,250X E269C

b. 0.19 Inch From Crack Origin

FIGURE 25. ELECTRON MICROGRAPHS OF REPLICAS OF AM 350 FATIGUE SURFACES PRODUCED AT 550 F, USING 40-KSI MEAN STRESS AND 30-KSI ALTERNATING STRESS

microscope. Micrographs of some of the areas studied are shown in Figure 26. Figure 26a was taken at the boundary between the fatigue crack and the tensile fracture. The tip of the fatigue crack has a typical striated appearance, while the initial portion of the tensile fracture is composed of both ductile and cleavage rupture. This can be seen more clearly in Figure 26b, which was taken slightly further ahead of the fatigue-crack tip. Figures 26c and 26d are typical ductile ruptures at a point 1/4 inch from the tip of the initial crack.

CONCLUSIONS

This program is an exploration of the fatigue behavior of two materials considered as possible skin materials for the supersonic transport; i.e., AM-350 CRT alloy and 8Al-1Mo-1V titanium alloy, triplex annealed. In the study, the base S-N relationships under certain conditions have been developed. In addition, fatigue-crack propagation and related residual static strength have been evaluated.

A large number of variables related to the mission environments have been studied, some to a limited extent. The program is to be extended into a second year, during which further evaluation of significant variables is planned. This report therefore essentially is a progress report; the conclusions in some cases are tentative.

On the basis of project activities to date, the following conclusions are reached:

(1) The fatigue behavior of the two materials, so far developed, does not suggest that either material should be ruled out as a possible material for the SST.

(2) Data concerned with effects of stressed exposure at elevated temperatures are available only on AM-350 alloy. From basic S-N type information, from crack-propagation data and from residual strength information, there does not seem to be a significant effect of stressed exposure (40 ksi, 550 F) for times of 1000 to 3000 hours. S-N data suggested there might be a slight reduction in strength; however, crack-propagation and residual-strength information did not substantiate this tendency. In the second year's work, another examination will be made for exposure times of 10,000 hours.

(3) The notched fatigue behavior of the two materials appears to be as good as or slightly better than that of 2024-T3 and 7075-T6, based upon the limited evaluations made. AM-350 alloy appears only slightly better than Ti-8Al-1Mo-1V alloy.

(4) Of the variables examined in the crack propagation studies of AM-350 alloy, the following can be stated:

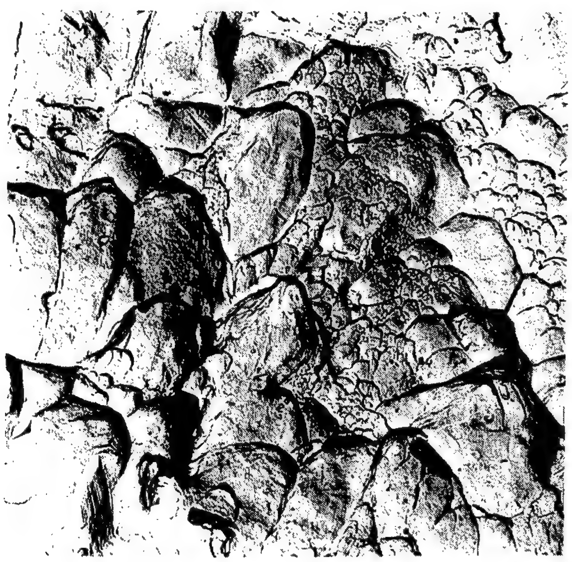
   (a) The rate of crack propagation increases with an increase in alternating stress amplitude.

2250X E270B

a.

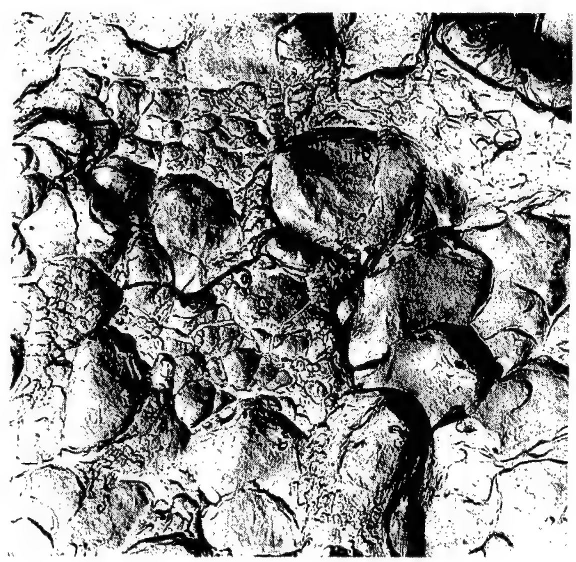
2250X E270D

b.



2250X E271B

c.



2250X E271C

d.

FIGURE 26. MICROGRAPHS OF FRACTURE SURFACES OF TENSION SPECIMENS FATIGUED AT ROOM TEMPERATURE

(b) The rate of crack propagation increases with crack length, at least to cracks where $\ell/W = 0.375$, even though the net-section stress is held constant within ± 10 per cent.

(c) Temperature appears to influence crack-propagation rate. The lower the temperature, the lower the rate (within the range -110 F to 550 F).

(d) The limited examination of orientation of specimens and of cycling rate was not sufficient to answer positively that these factors are important influences on crack propagation.

(5) Of the variables examined in the residual-static-strength studies of AM-350 alloy, the following can be stated:

(a) The residual static strength of AM-350 sheet is reduced by fatigue cracks oriented perpendicular to the tensile axis; the reduction is greater, the greater the crack length. The reduction is not as great as that reported for AM-355 or PH 15-7Mo.

(b) Temperatures above (550 F) and below (-110 F) room temperature were found to decrease static strength of fatigue-cracked specimens.

(c) Fatigue cracks in transverse specimens were more detrimental than were cracks in longitudinal specimens.

(d) In regard to fatigue conditions employed to introduce the fatigue cracks, it appears that stress amplitude, fatigue-cracking temperature, and cyclic speed have no effect on residual strength.

(6) Examination of AM-350 fracture surface replicas with the electron microscope supports the hypothesis that each fatigue cycle produces one striation on the fracture surface. However, such striations are not uniform in spacing or in orientation for a given set of fatigue conditions; this suggests that fatigue-crack growth is not as smooth and uniform as is observed on a macroscopic scale.

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APPENDIX A

TENSILE DATA ON AM-350 AND Ti-8Al-Mo-1V SHEETS

TABLE A-1. MANUFACTURER'S DATA ON AM-350 CRT STAINLESS STEEL

Material:	AM-350 stainless steel, CRT condition
Number of Sheets:	Three, designated XA5, XA7, XA8
Size of Sheet:	36 x 96 x 0.050 in.
Heat:	55431

Chemical Analysis		
Element	Weight, per cent	Mechanical Properties
C	0.096	Yield Strength, 183,970 psi
Mn	0.75	Tensile Strength, 233,460 psi
P	0.015	Elongation, 13.0 per cent
S	0.010	Hardness, 48 R_C
Si	0.27	
Cr	16.64	
Ni	4.30	
Mo	2.79	
N_2	0.096	

TABLE A-2. MANUFACTURER'S DATA ON Ti-8Al-1Mo-1V ALLOY

Material:	8Al-1Mo-1V titanium alloy
Condition:	Triplex annealed 8 hours, 1450 F, furnace cool +5 minutes, 1850 F, air cool +15 minutes, 1375 F, air cool
Number of Sheets:	Three, designated TA6, TA7, TA8
Size of Sheets:	36 x 96 x (0.038 to 0.049) inch

Chemical Analysis		Mechanical Properties		
Element	Weight, per cent	Yield Strength, psi	Tensile Strength, psi	Elongation, per cent
C	0.023	130,300 min	142,300 min	11 min
Fe	0.09	141,100 max	152,600 max	16 max
N_2	0.013	133,000 avg	147,000 avg	13 avg
Al	7.6			
Va	1.0			
Mo	1.1			
H_2	0.010-0.014			

TABLE A-3. SUMMARY OF TENSILE TEST DATA ON THREE SHEETS OF AM-350 CRT STEEL, HEAT 55431

Specimen[a]	Test Temp, F	Ultimate Tensile Strength, ksi	0.2 Per Cent Offset Yield Strength, ksi	Elongation in 2 Inches, per cent	Modulus of Elasticity, 10^6 psi
			(Sheet XA6)		
621 (L)	RT		-	-	-
622 (T)	"	240	203	15.5	29.4
623 (T)	"	238	201	15.5	29.1
624 (L)	"	232	222	23.0	27.4
625 (T)	"	236	199	12.0	29.0
262 (T)	"	233	203	9.5	29.2
627 (L)	"	234	220	22.0	27.6
			(Sheet XA7)		
721 (L)	"	235	219	22.3	27.3
722 (T)	"	234	199	12.7	29.1
723 (T)	"	238	199	16.5	29.2
724 (L)	"	232	220	20.5	28.5
725 (T)	"	237	201	12.0	29.2
726 (T)	"	238	202	14.0	30.1
727 (L)	"	235	220	21.0	28.8
			(Sheet XA8)		
821 (L)	"	234	221	18.5	28.2
822 (T)	"	234	202	9.0	30.0
823 (T)	"	237	201	14.0	30.6
824 (L)	"	233	220	20.0	27.5
825 (T)	"	232	200	15.0	30.0
826 (T)	"	234	199	11.5	29.1
827 (L)	"	231	222	21.5	26.8
828 (L)	-100	273	221	20.5	27.0
829 (L)	-100	272	221	20.0	29.2
8210 (L)	+550	202	185	4.0	25.4
8211 (L)	+550	199	183	3.5	25.2

(a) Specimens oriented parallel to the rolling direction (longitudinal) are designated (L); specimens oriented normal to the rolling direction (transverse) are designated (T).

TABLE A-4. SUMMARY OF TENSILE TEST DATA ON THREE SHEETS OF Ti-8Al-1Mo-1V

Specimen[a]	Test Temp, F	Thickness, inch	Ultimate Tensile Strength, ksi	0.2 Per Cent Offset Yield Strength, ksi	Elongation, in 2 Inches, per cent	Modulus of Elasticity, 10^6 psi
			Sheet TA6			
TA 621 (L)	RT	0.0493	151	137	14	18.7
TA 622 (T)	"	0.0483	142	130	17	17.3
TA 623 (T)	"	0.0480	143	131	12	17.1
TA 624 (L)	"	0.0476	153	138	13	19.3
TA 625 (T)	"	0.0467	143	131	15	17.1
TA 626 (T)	"	0.0463	143	130	14.5	17.4
TA 627 (L)	"	0.0472	148	139	17	19.0
			Sheet TA7			
TA 721 (L)	RT	0.0430	153	139	11	18.4
TA 722 (T)	"	0.0434	144	130	10	17.0
TA 723 (T)	"	0.0438	144	132	9	17.3
TA 724 (L)	"	0.0441	154	143	14	19.1
TA 725 (T)	"	0.0435	143	132	9	17.3
TA 726 (T)	"	0.0426	146	133	9	18.3
TA 727 (L)	"	0.0450	153	140	14	18.7
			Sheet TA8			
TA 821 (L)	RT	0.0402	-	142	10	18.7
TA 822 (T)	"	0.0410	146	132	14	17.2
TA 823 (T)	"	0.0420	146	133	10	17.4
TA 824 (L)	"	0.0426	155	140	11	18.7
TA 825 (T)	"	0.0424	145	132	9	17.4
TA 826 (T)	"	0.0412	147	134	13	17.7
TA 827 (L)	"	0.0398	151	138	12	18.3
TA 828 (L)	-100	0.0415	178	165	11.5	20.1
TA 829 (L)	-100	0.0415	179	166	12.5	20.0
TA 8210 (L)	+550	0.0415	125	98	9.0	16.0
TA 8211 (L)	+550	0.0415	124	97	10.0	17.4

APPENDIX B

TABLES OF STRESS-LIFETIME DATA

TABLE B-1. STRESS-LIFETIME DATA FOR UNNOTCHED AM-350 SPECIMENS

Specimen	Maximum Stress, ksi	Number of Cycles to Failure
	Room Temperature, 20-Ksi Mean Stress	
6166	165.0	16,000
6116	140.0	28,600
6122	130.0	39,000
6159	130.0	81,000
6111	120.0	190,000
8116	120.0	105,000
8120	115.0	170,000
6126	115.0	163,000
8114	110.0	177,700
6167	110.0	89,000
6160	110.0	99,800
8113	110.0	179,800
6127	106.0	77,000
8126	105.0	149,800
8124	102.0	14,928,900 D. N. F.[a]
8160	100.0	65,400
7112	100.0	153,500
8170	95.0	89,000
8162	95.0	15,428,600 D. N. F.
7123	95.0	10,362,400 D. N. F.
7117	90.0	13,609,500 D. N. F.
8161	90.0	12,340,000 D. N. F.
	Room Temperature, 40-Ksi Mean Stress	
7127	170.0	10,000
7121	165.0	16,000
8127	160.0	16,800
8112	158.0	22,000
8122	150.0	21,400
6118	146.0	46,300
8121	140.0	41,000
6123	140.0	40,100
7119	132.5	57,700
8117	130.0	286,500
7111	130.0	74,000
7116	125.0	4,294,900
8111	125.0	133,400
6162	120.0	72,400

TABLE B-1. (Continued)

Specimen	Maximum Stress, ksi	Number of Cycles to Failure
	Room Temperature, 40-Ksi Mean Stress (Continued)	
6125	120.0	11,642,400 D. N. F.
8164	120.0	11,233,000 D. N. F.
7124	120.0	148,200
8155	115.0	10,000,000 D. N. F.
6115	110.0	14,686,000 D. N. F.
	-110 F, 40-Ksi Mean Stress	
6119	200.0	16,000
6163	167.0	45,000
6114	152.0	128,000
6164	146.0	138,000
7126	143.0	199,000
6124	140.0	221,200
6117	130.0	1,213,100
7115	128.0	687,000
8118	123.0	2,467,000 G. F.[b]
	550 F, 40-Ksi Mean Stress	
7122	165.0	4,700
7125	150.0	11,000
7118	135.0	20,000
8123	120.0	48,000
6165	115.0	39,000
7120	115.0	50,000
8115	110.0	10,020,000 D. N. F.

(a) D.N F. (did not fail): experiment was stopped at indicated number of cycles.

(b) G.F. (grip failure): specimen failed in machine grip.

TABLE B-2. STRESS-LIFETIME DATA FOR NOTCHED (K_t = 4.0) AM-350 SPECIMENS

Specimen	Maximum Stress, ksi	Number of Cycles to Failure
	Room Temperature, 20-Ksi Mean Stress	
8137	90.0	7,000
7128	80.0	13,000
7129	70.0	21,000
7154	60.0	34,400
6140	50.0	90,000
7133	47.5	10,612,900 D.N.F.
6142	45.0	334,000
6136	45.0	15,045,700 D.N.F.
6137	42.5	10,019,800 D.N.F.
6147	40.0	11,810,000 D.N.F.
	Room Temperature, 40-Ksi Mean Stress	
7131	120.0	2,500
6143	98.0	10,000
6156	80.0	19,500
6158	70.0	30,000
7130	60.0	173,000
8138	57.5	72,000
6144	56.6	1,484,000
8133	55.0	10,248,000 D.N.F.
	-110 F, 40-Ksi Mean Stress	
7135	120.0	1,000
7163	105.0	7,000
7164	90.0	25,000
7132	75.0	58,000
6139	70.0	120,000
7158	67.5	177,000
6133	65.0	1,062,000 G.F.
6148	65.0	5,959,000 D.N.F.
	550 F, 40-Ksi Mean Stress	
6138	100.0	2,500
6135	88.0	3,500
6145	75.0	11,000
6134	70.0	27,000
8142	65.0	58,000
8143	63.7	487,000 G.F.
8141	63.7	38,000
7162	62.5	12,598,000 D.N.F.
7157	60.0	10,044,800 D.N.F.

TABLE B-2. (Continued)

Specimen	Maximum Stress, ksi	Number of Cycles to Failure
	-110 F, 40-Ksi Mean Stress, Previously Exposed to 550 F and 40-Ksi Stress for 1000 Hours	
6153	105.0	6,200
7167	89.0	20,000
6150	75.0	54,000
6130	65.0	166,000
7152	62.5	190,000
7168	61.3	3,000,000 D.N.F.
7140	60.0	2,713,600 D.N.F.
	-100 F, 40-Ksi Mean Stress, Previously Exposed to 550 F and 40-Ksi Stress for 3000 Hours	
7153	105.0	5,500
6139	89.0	21,000
7149	75.0	71,500
8130	65.0	290,000
	550 F, 40-Ksi Mean Stress, Previously Exposed for 1000 Hours to 550 F and 40-Ksi Stress	
6150	88.0	3,900
7136	75.0	13,100
6132	70.0	23,200
7166	67.5	34,000
7144	65.0	2,281,000
6157	65.0	39,000
7139	63.7	1,107,000
6149	63.7	35,000
6152	62.0	39,500
7137	60.0	5,412,700

TABLE B-3. STRESS LIFETIME DATA FOR UNNOTCHED Ti-8Al-1Mo-1V ALLOY

Specimen	Maximum Stress, ksi	Number of Cycles to Failure
	Room Temperature, 25-Ksi Mean Stress	
8123	140.0	6,900
6127	120.0	19,000
8127	110.0	29,600
6126	95.0	55,000
8115	90.0	106,000
6116	90.0	90,000
8124	87.5	132,000
6122	85.0	361,000
6111	82.5	1,979,300
7124	81.0	2,508,000
6114	80.0	1,091,400
6124	80.0	11,517,000 D. N. F.
	-110 F, 25-Ksi Mean Stress	
6115	160.0	14,300
8120	150.0	24,500
8119	140.0	47,800
8116	120.0	68,200
7121	110.0	131,000
6117	100.0	306,200
7125	95.0	308,700
6118	90.0	813,000
6123	85.0	3,434,600 D. N. F.
	550 F, 25-Ksi Mean Stress	
6163	120.0	1,900
6125	110.0	7,500
8125	95.0	33,000
8122	95.0	38,400
6112	85.0	50,000
7126	85.0	49,500
6120	82.5	1,049,000
8118	80.0	162,000
6113	78.5	3,316,600
8117	77.0	5,716,800
8126	76.0	2,638,400

TABLE B-4. STRESS LIFETIME DATA FOR NOTCHED (K_t = 4.0) Ti-8Al-1Mo-1V ALLOY

Specimen	Maximum Stress, ksi	Number of Cycles to Failure
	Room Temperature, 25-Ksi Mean Stress	
6158	85.0	2,400
7113	70.0	5,000
6128	60.0	12,000
8148	50.0	26,000
7111	40.0	94,000
7118	35.0	267,000
8111	33.7	236,000
7119	33.0	3,098,000
6145	32.5	10,000,000 D.N.F.
8135	30.0	11,483,600 D.N.F.
6181	39.0	83,500
6180	39.0	68,000
	-110 F, 25-Ksi Mean Stress	
8132	85.0	2,600
7120	77.5	5,100
8138	70.0	11,500
7114	60.0	16,700
8150	50.0	39,000
8114	45.0	73,000
8133	45.0	54,000
8134	42.5	722,000
6132	42.5	2,965,400 D.N.F.
7117	40.0	2,760,800 D.N.F.
6134	35.0	2,810,400 D.N.F.
	550 F, 25-Ksi Mean Stress	
8149	70.0	2,300
7115	60.0	7,500
8147	50.0	25,800
7112	40.0	99,400
8130	35.0	10,197,500 D.N.F.
8131	35.0	14,379,400 D.N.F.
7116	32.5	12,053,000 D.N.F.
6136	30.0	11,174,000 D.N.F.

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-110 F to 550 F. Similarly, the effect of prior stressed exposure at 550 F on fatigue strength has been evaluated for exposure times up to 3000 hours for AM-350 alloy. Crack-propagation studies were conducted on center-notched sheet specimens of AM-350 alloy with variables evaluated such as alternating stress amplitude, test temperature, cyclic rate, specimen orientation, and prior stressed exposure. As expected, alternating stress amplitude and test temperature appreciably affect crack-propagation rates, whereas, for times up to 1000 hours, stressed exposure was not important. Residual-static-strength measurements also were made from center-cracked specimens of AM-350 alloy. Crack length and test temperature were found to be important variables, whereas stressed exposure and conditions under which the fatigue cracks were grown were found to be unimportant variables.

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-110 F to 550 F. Similarly, the effect of prior stressed exposure at 550 F on fatigue strength has been evaluated for exposure times up to 3000 hours for AM-350 alloy. Crack-propagation studies were conducted on center-notched sheet specimens of AM-350 alloy with variables evaluated such as alternating stress amplitude, test temperature, cyclic rate, specimen orientation, and prior stressed exposure. As expected, alternating stress amplitude and test temperature appreciably affect crack-propagation rates, whereas, for times up to 1000 hours, stressed exposure was not important. Residual-static-strength measurements also were made from center-cracked specimens of AM-350 alloy. Crack length and test temperature were found to be important variables, whereas stressed exposure and conditions under which the fatigue cracks were grown were found to be unimportant variables.

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